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1954

Number

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Number

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Number

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Number

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Number

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AUTHOR INDEX

Contribution No.

ARRHENIUS, GUSTAF
  Origin and accumulation of aluminosilicates in the ocean . . . 730

AUSTIN, THOMAS S.
  (with Marston C. Sargent) Biologic economy of coral reefs, Bikini and nearby atolls, Marshall Islands . . . 703

BASCOM, WILLARD N.
  Characteristics of natural beaches . . . 674
  The control of stream outlets by wave refraction . . . 675

BERNER, LEO D.
  On the previously undescribed aggregate form of the pelagic tunicate *Ritteriella picteti* (Apstein) (1904) . . . 686

BIEN, GEORGE S.
  High-frequency titration of micro quantities of chloride and sulfate . . . 691

BLACK, JOHN D.
  (and Carl L. Hubbs) Status and synonymy of the American percid fish, *Hadropterus scierus* . . . 687

BRAMLETTE, M. N.
  (and W. R. Riedel) Stratigraphic value of discoasters and some other microfossils related to recent coccolithophores . . . 717

CARRIER, G. F.
  (and W. H. Munk) On the diffusion of tides into permeable rock . . . 659

COX, CHARLES
  (and Walter Munk) Statistics of the sea surface derived from sun glitter . . . 731
  (and Walter Munk) Measurement of the roughness of the sea surface from photographs of the sun's glitter . . . 737

DIETZ, ROBERT S.
  Marine geology of the northwestern Pacific: description of Japanese bathymetric chart 6901 . . . 664
  (with Robert F. Dill and Harris Stewart) Deep-sea channels and delta of the Monterey submarine canyon . . . 669
  (and Henry W. Menard and Edwin L. Hamilton) The echograms of the Mid-Pacific Expedition . . . 721
  Methods of exploring the ocean floor: *Discussion* . . . 679

DILL, ROBERT F.
  (and Robert S. Dietz and Harris Stewart) Deep-sea channels and delta of the Monterey submarine canyon . . . 669
  (with Henry W. Menard, E. L. Hamilton, D. G. Moore, George Shumway, M. Silverman, and H. B. Stewart) Underwater mapping by diving geologists . . . 671

Contribution No.

ECKART, CARL
Wave measurements: *Discussion* 739b

EWING, GIFFORD
(with Raymond M. Gilmore) Calving of the California grays 697

FISHER, ROBERT L.
(and Roger Revelle) A deep sounding from the southern hemisphere 727
On the sounding of the trenches 736

FOLSOM, THEODORE R.
(with George F. McEwen and Martin W. Johnson) A statistical analysis of the performance of the Folsom plankton sample splitter, based upon test observations 689
Oceanographic instruments for measuring temperature: *Discussion* 678b

FOX, DENIS L.
(and Carl H. Oppenheimer and James S. Kittredge) Microfiltration in oceanographic research II. Retention of colloidal micelles by adsorptive filters and by filter-feeding invertebrates: proportions of dispersed organic to dispersed inorganic matter and to organic solutes 662
(and Norman Millott) A biliverdin-like pigment in a skull and vertebrae of the ocean skipjack, *Katsuwonus pelamis* (Linnaeus) 677
(with Norman Millott) The pigmentation of the jellyfish, *Pelagia noctiluca* 676
An acidogenic carotenoid in a bathypelagic nemertean worm 690
(and Norman Millott) The pigmentation of the jellyfish, *Pelagia noctiluca* (forskål) var. *panopyra* Péron and Lesueur 695
Organic detritus in the metabolism of the sea 708
(and Carl H. Oppenheimer) The riddle of sterol and carotenoid metabolism in muds of the ocean floor 718

FRAUTSCHY, JEFFREY D.
Methods of exploring the ocean floor: *Discussion* 679a

GILMORE, RAYMOND M.
(and Gifford Ewing) Calving of the California grays 697

GOLDBERG, EDWARD D.
(with Clare C. Patterson and Mark G. Inghram) Isotopic compositions of Quaternary leads from the Pacific Ocean 666
Marine geochemistry 1: Chemical scavengers of the sea 692
(with George J. Lewis) Iron in marine water 714
(with Pampapathi K. Rao) Utilization of dissolved calcium by a Pelcypod 722

GOSSARD, EARL
(and Walter Munk) On gravity waves in the atmosphere 720

HAMILTON, EDWIN L.
(with H. W. Menard, and R. F. Dill, D. G. Moore, George Shumway, M. Silverman, and H. B. Stewart) Underwater mapping by diving geologists 671
(with Robert S. Dietz and Henry Menard) The echograms of the Mid-Pacific Expedition 721

Contribution No.

HAND, CADET
Three Pacific species of "Lar" (including a new species), their hosts, medusae, and relationships. (Coelenterata, Hydrozoa) 668

HEDGPETH, JOEL W.
A problem in oyster taxonomy 682
On the phylogeny of the pycnogonida. 701

HUBBS, CARL L.
(and R. R. Miller) Studies of cyprinodont fishes. XXI. *Glaridodon latidens*, from northwestern Mexico, redescribed and referred to *Poeciliopsis* 681
(and John D. Black) Status and synonymy of the American percid fish *Hadropterus scierus* 687
David Starr Jordan 712
(with Robert Rush Miller) An erroneous record of the California killifish *(Fundulus parvipinnis)* from Cabo San Lucas, Baja California 705
Establishment of a forage fish, the red shiner *(Notropis lutrensis)* in the lower Colorado river system 715
Western gull, with symmetrical wing patches, resembling aberrant Heermann gulls 724
A juvenile gadid fish from the Labrador sea representing a species of *Gaidropsarus* apparently new for North America. 733
(and Laura C. Hubbs) Data on the life history, variation, ecology, and relationships of the kelp perch, *Brachyistius frenatus*, an embiotocid fish of the Californias. 688

HUBBS, LAURA C.
(with Carl L. Hubbs) Data on the life history, variation, ecology, and relationships of the kelp perch, *Brachyistius frenatus*, an embiotocid fish of the Californias. 688

INMAN, DOUGLAS L.
Beach and nearshore processes along the southern California coast 657

INGHRAM, MARK G.
(with Clare C. Patterson and Edward D. Goldberg) Isotopic compositions of Quaternary leads from the Pacific Ocean 666

ISAACS, JOHN D.
Considerations of oceanographic instrumentation 678

JOHNSON, MARTIN W.
Some outlines of plankton concentration in the eastern and tropical Pacific 658
(with George F. McEwen and Theodore R. Folsom) A statistical analysis of the performance of the Folsom plankton sample splitter, based upon test observations 689
Plankton of the northern Marshall Islands. Bikini and nearby atolls, Marshall Islands 702
Studies on plankton of the Bering and Chukchi Seas and adjacent areas 710

Contribution No.

KITTREDGE, JAMES S.
(with D. L. Fox and C. H. Oppenheimer) Microfiltration in oceanographic research: II. Retention of colloidal micelles by adsorptive filters and by filter-feeding invertebrates; proportions of dispersed organic to dispersed inorganic matter and to organic solutes 662

LEWIS, GEORGE J.
(and Edward D. Goldberg) Iron in marine waters 714

LIEBERMANN, LEONARD N.
Acoustic instrumentation as a tool in oceanography: *Discussion* 678c

MAGNESS, T. A.
The spectral response of a quadratic device to non-Gaussian noise 713

McEWEN, GEORGE F.
(and Martin W. Johnson and Theodore R. Folsom) A statistical analysis of the performance of the Folsom plankton sample splitter, based upon test observations 689

McGOWAN, JOHN A.
Observations on the sexual behavior and spawning of the squid, *Loligo opalescens*, at La Jolla, California 670

McHUGH, J. L.
Geographic variation in the Pacific herring 667
Distribution and abundance of the diatom *Ethmodiscus rex* off the west coast of North America 706

MENARD, HENRY W.
(and R. F. Dill, E. L. Hamilton, D. G. Moore, George Shumway, M. Silverman, and H. B. Stewart) Underwater mapping by diving geologists 671
(with Robert S. Dietz and E. L. Hamilton) Echograms of the Mid-Pacific Expedition 721

MENZIES, ROBERT J.
(and Milton A. Miller) Key to chelifera and the suborders of the isopoda 683
The comparative biology of reproduction in the wood-boring isopod crustacean *Limnoria* 740

MILLER, MILTON A.
(and Robert J. Menzies) Key to chelifera and the suborders of the isopoda 683

MILLER, ROBERT RUSH
(with Carl L. Hubbs) Studies of cyprinodont fishes. XXI. *Glaridodon latidens* from northwestern Mexico, redescribed and referred to *Poeciliopsis* 681
(and Carl L. Hubbs) An erroneous record of the California killfish *(Fundulus parvipinnis)* from Cabo San Lucas, Baja California 705

Contribution No.

MILLOTT, NORMAN
(and Denis L. Fox) The pigmentation of the jellyfish, *Pelagia noctiluca* 676
(with Denis L. Fox) A bilverdin-like pigment in a skull and vertebrae of the ocean skipjack, *Katsuwonus pelamis* (Linnaeus) 677
(and Denis L. Fox) The pigmentation of the jellyfish, *Pelagia noctiluca* (forskål) var. *panopyra* Péron and Lesueur 695

MINTZ, YALE
(and Walter Munk) The effect of winds and bodily tides on the annual variation in the length of day 693

MONTGOMERY, R. B.
(and Warren S. Wooster) Thermosteric anomaly and the analysis of serial oceanographic data. 735

MOORE, DAVID G.
(with Francis Shepard) Sedimentary environments differentiated by coarse-fraction studies 726
Submarine geology of the San Pedro shelf 699
(with H. W. Menard, R. F. Dill, E. L. Hamilton, George Shumway, M. Silverman, and H. B. Stewart) Underwater mapping by diving geologists 671

MUNK, WALTER H.
Air-sea boundary processes. 680a
(with Yale Mintz) The effect of winds and bodily tides on the annual variation in the length of the day. 693
(with Earl Gossard) On gravity waves in the atmosphere 720
(with Charles Cox) Statistics of the sea surface derived from sun glitter 731
(with Charles Cox) Measurement of the roughness of the sea surface from photographs of the sun's glitter 737
(with G. F. Carrier) On the diffusion of tides into permeable rock 659
(and Marston C. Sargent) Adjustment of Bikini atoll to ocean waves 698
Wave measurements: *Discussion* 739a

NASU, NORIYUKI
Taiyo no kaitei. 716

NORRIS, KENNETH S.
(with William G. Reeder) The distribution, type locality, and habits of the fish-eating bat, *Pizonyx vivesi* 665

NORTH, WHEELER J.
Size distribution, erosive activities, and gross metabolic efficiency of the intertidal snails, *Littorina planxis* and *L. scutulata* 685

OPPENHEIMER, CARL
Disease as a factor in natural mortality of marine fish 656
(with D. L. Fox and J. S. Kittredge) Microfiltration in oceanographic research. II. Retention of colloidal micelles by adsorptive filters and by filter-feeding invertebrates; proportions of dispersed organic to dispersed inorganic matter and to organic solutes 662

Contribution No.

OPPENHEIMER, CARL (continued)
(with Denis L. Fox) The riddle of sterol and carotenoid metabolism in muds of the ocean floor. 718
The effect of marine bacteria on the development and hatching of pelagic fish eggs and the control of such bacteria by antibiotics. 732

PARKER, FRANCES L.
(with Fred B Phleger) Gulf of Mexico foraminifera 660
Distribution of the foraminifera in the northeastern Gulf of Mexico 709

PATTERSON, CLAIRE C.
(and E. D. Goldberg and Mark G. Inghram) Isotopic compositions of Quaternary leads from the Pacific Ocean 666

PHLEGER, FRED B
(and Frances L. Parker) Gulf of Mexico foraminifera 660
Ecology of foraminifera and associated micro-organisms from Mississippi Sound and environs 694
Foraminifera and deep-sea research 719

RAITT, RUSSELL W.
Geophysical measurements 680
The 1950 seismic refraction studies of Bikini and Kwajalein atolls and Sylvania guyot 723

RAKESTRAW, NORRIS W.
Chemical measurements: *Discussion* 678d

RAO, K. PAMPAPATHI
(and Edward D. Goldberg) Utilization of dissolved calcium by a Pelecypod 722

RECHNITZER, ANDREAS B.
Status of the wood ibis in San Diego County, California 734

REEDER, WILLIAM G.
(and Kenneth S. Norris) The distribution, type locality, and habits of the fish-eating bat, ... 665

REVELLE, ROGER
Considerations of oceanographic instrumentation: *Discussion* 678a
Methods of exploring the ocean floor: *Discussion* 679b
The earth beneath the sea — geophysical exploration under the ocean 684
Fluctuating fishery stocks: what we know about this world-wide riddle. Part II — Other contributing factors; The green pastures of the sea. 704
(with Robert L. Fisher) A deep sounding from the southern hemisphere 727
Foreword, Geology of Bikini and nearby atolls, Part I. 729

RICHARDS, ADRIAN F.
Volcanic eruptions of 1953 and 1948 on Isabella Island, Galapagos Islands, Ecuador 741

Contribution No.

RIEDEL, WILLIAM R.
The age of the sediment collected at Challenger (1875) Station 225 and the distribution of *Ethmodiscus rex* (Rattray). 696
(with M. N. Bramlette) Stratigraphic value of discoasters and some other microfossils related to recent coccolithophores. 717

ROBINSON, MARGARET K.
Sea temperature in the Marshall Islands area, Bikini and nearby atolls, Marshall Islands 700

SARGENT, MARSTON C.
(with Walter H. Munk) Adjustment of Bikini atoll to ocean waves 698
(and Thomas S. Austin) Biologic economy of coral reefs — Bikini and nearby atolls, Marshall Islands 703

SHEPARD, FRANCIS P.
High-velocity turbidity currents, a discussion 673
Nomenclature based on sand-silt-clay ratios 725
(and D. G. Moore) Sedimentary environments differentiated by coarse-fraction studies 726

SHUMWAY, GEORGE
(with H. W. Menard, R. F. Dill, E. L. Hamilton, D. G. Moore, M. Silverman, and H. B. Stewart) Underwater mapping by diving geologists 671
Carnegie ridge and Cocos ridge in the east equatorial Pacific 738

SILVERMAN, M.
(with H. W. Menard, R. F. Dill, E. L. Hamilton, D. G. Moore, George Shumway, and H. B. Stewart) Underwater mapping by diving geologists 671

SNODGRASS, FRANK E.
Wave measurements 739

STEWART, HARRIS B.
(with H. W. Menard, R. F. Dill, E. L. Hamilton, D. G. Moore, George Shumway, and M. Silverman) Underwater mapping by diving geologists 671
(with Robert F. Dill and Robert S. Dietz) Deep-sea channels and delta of the Monterey submarine canyon 669

SWEENEY, BEATRICE M.
Gymnodinium splendens, a marine dinoflagellate requiring vitamin B_{12} 728

VAN DORN, WILLIAM G.
Wind stress on an artificial pond 663

WOOSTER, WARREN S.
Recent oceanographic exploration in the north and equatorial Pacific Ocean 672
(with R. B. Montgomery) Thermosteric anomaly and the analysis of serial oceanographic data. 735

ZOBELL, CLAUDE
Marine bacteria and fungi in the Gulf of Mexico 661
Some effects of high hydrostatic pressure on apparatus observed on the Danish Galathea Deep-sea Expedition 707

656

DISEASE AS A FACTOR IN NATURAL MORTALITY OF MARINE FISH

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TIPOGRAFIA FAUSTO FAILLI ROMA

DISEASE AS A FACTOR IN NATURAL MORTALITY OF MARINE FISH [1,2]

Although there is an active and effective interest in the diseases of fresh-water fish, and a correspondingly useful body of literature in this field, there is much less interest, and a much sparser literature on the diseases of marine fish. The interest in the diseases of fresh-water fish grew out of practical and economic necessity: in Europe, and more recently in North America, the losses caused by disease have proved troublesome and expensive and it was natural that investigators should turn their attention to a study of these diseases and to a search for means of controlling them.

The first studies of fish diseases were made on infected fish in the restricted natural habitats of ponds and streams where, from time to time, epidemics have occurred, destroying stock almost entirely (Babes and Riegler, 1903). As the practice of fish culture increased there developed techniques for the control of disease. It may be said that fish culturists now are familiar with a range of fish diseases, and have available a useful battery of drugs and techniques with which to combat and control them. But it must be stressed that this situation prevails only for cultivated stock within restricted environments, and that it relates to a few species of fish whose condition, in health and disease, is familiar to the culturist who, moreover, has the stock under constant observation. As a consequence, the literature on fish diseases relates almost exclusively to those of fresh-water fish. The classic works on the subject are those of Plehn (1924) and Schäperclaus (1941) which summarize the literature up to 1940.

The natural environment of a lake, pond or stream, usually provides optimal conditions for the growth and multiplication of microorganisms. Consequently it is not uncommon to find there rather large bacterial populations. While many people recognize this, very few know that the same holds true for a marine environment, and that the presence of salts is not a limiting factor. Salt water has been proved to be a natural habitat for bacteria and other microbes which may cause diseases in fishes.

Parasitism of fish has received much attention as is shown by the number of papers concerning copepod, helminth and other parasites to be found listed by the abstracting and bibliographic services. For the purposes of this paper, however, we are not considering this aspect of mortality but that which is understood by the term pathology; and in this field relatively few articles on micro-organism caused diseases of marine fish appear in the literature (Moore 1912; Aronson, 1926; Bruun and Heiberg, 1932; ZoBell and Welles, 1943; Schäperclaus, 1941; Nigrelli and Hunter, 1945; Rucker, 1949; Hodgkiss

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[2] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 656.

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and Shewan, 1950). Fungus infections in marine fishes have been occasionally reported (Fish, 1934 ; Sproston, 1947) .

Although approximately 70 percent of the earth's surface is covered by the oceans, relatively few scientists are engaged in studying the sea, and of these very few indeed are marine microbiologists. Interest has lagged because of the obviously limited practical application of such research and because there are few organizations where the necessary specialized training is offered. But the paucity of attention given to the diseases of marine fish may perhaps be best ascribed to two considerations ; firstly, that the resources of the sea have seemed inexhaustible, and secondly, that even if disease-causing organisms might prove to be an important factor in these environments, of which few people were convinced, it seemed even less likely that anything could be done about them. But now that we begin to recognize some of the limitations to these resources, and as we look deeper into the intricacies of the ecosystems of which our commercial species form part, we begin to suspect that perhaps these diseases are more significant than we had thought, and that they merit closer attention.

Many people have doubted the presence of widespread marine fish diseases. This is quite easy to understand because, for two general reasons, such diseases may easily pass unnoticed. The first is concerned with the physical properties of water. The change in refractive index between water and air causes the visual properties of objects to be changed, and, in consequence, infectious growths which may be recognized on a fish when it is in water, may become inconspicuous or invisible when it is removed into the air. To this is added the complication that lesions on fish are not easily observed in their natural habitat because it is quite difficult to get within observation distance.

During the summer of 1952 at the Scripps Institution of Oceanography, Conrad Limbaugh made an investigation of certain fish in their natural habitats. Using a diving unit which allowed him freedom in the water for periods up to 45 minutes and at depths to 100 feet, he estimated that from 5 to 10 percent of fish of several types had lesions involving the scales, tail and fins. Several of the infected fish were speared and brought to the surface for bacterial examination. In the air the fish appeared normal and the diver had to point out the places where he had seen the infections. Later examination of the lesions by phase microscopy and by cultural methods revealed that large numbers of bacteria were present. These observations demonstrated that an observer cannot easily see the infected part of the fish when it is out of water and, therefore, lesions may be overlooked in routine observations in the laboratory and even in the field. Similar infected fish were prevalent during the summer of 1953.

The second reason which might explain why fish diseases have passed unnoticed is that natural predation would tend to remove infected fish from observation. An infected fish is usually less active and soon falls prey to its natural enemies. If this were a substantial effect, constituting a high rate of natural mortality for such fish, relatively few of them would be caught, and this would suggest that they are scarce in nature. Mr. Limbaugh noted that most fish with lesions took cover sooner than their healthy neighbors, as though they sensed their incapacity.

Careful observations of fish from three marine aquaria along the coast of southern California have demonstrated that infections are common, especially when the water temperature increases during the warm summer months. The lesions of such infected fish are not detected by ordinary observation, but only by the most careful examination.

Several types of external lesion have been noted in marine fishes in salt-water aquaria. It is common to find tail-rot or fin-rot, a type of disease which is usually slow but persistent, where the fins and tail erode away. A white cotton-like growth may involve the bases of the scales, which are thus pushed away from the body, making the integument appear rough in places. Necrotic lesions of the integument may be present. Infections in fish eyes cause the lens to become opaque. Occasionally, the formation of gas in the chamber of the eye tends to make the eye appear "popped" Some fish are seen in which the eye lens has fallen out as the result of an infection, and the socket healed shut. External bleeding of the skin, believed to be caused by bacterial infection, has been observed and appears to cause the death of the fish. Other fish have been observed to lose their equilibrium and to swim in various abnormal positions.

At times fish lesions caused by *Pseudomonas ichthyodermis* have reached almost epidemic proportions. During the summer months of 1952 and 1953, it has been possible to isolate this organism from the ocean near shore and from the marine aquarium at the Scripps Institution. At the same time, a high percentage of the fish in the aquarium had characteristic lesions although apparently only certain species of fish were sensitive to the bacteria. It has been found that this organism is inhibited by penicillin.

As a result of diseases and the lack of knowledge for their control, many valuable fish are lost in marine aquaria each year. During the summer of 1952, one aquarium on the west coast of California lost a large part of the fish stock because of disease. Many valuable fish could have been saved if the aquarium keepers had known how to recognize and combat the infections.

It is likely that certain diseases are carried into aquaria by newly caught fish, especially those which have been injured during capture. The practice of isolating or quarantining new fish for suitable periods of time is of great importance to the maintenance of a healthy aquarium. Information regarding the length of isolation, and prophylactic treatments of marine fish, is very scanty and offers interesting problems for properly trained microbiologists. In any event it is obvious that whatever the deficiencies of aquaria as a means of investigating other aspects of fish biology, they offer admirable opportunity of studying diseases.

Thus, while the foregoing evidence suggests that the reason for the neglect of this field of study most probably is that various factors have operated to conceal the effects of disease-causing organisms on mature fish, there is useful evidence concerning disease effects in young stages.

Ahlstrom (1948) has reported abnormalities in up to 45 percent of sardine eggs collected during a study of the Pacific coast sardine. It is possible that marine bacteria may have been responsible for a proportion of the abnormalities.

It is significant that about 65 percent of the known species of marine bacteria attack protein. Recent experiments by one of us (C. H. O.) indicate that bacteria may have adverse effects on the eggs of sardine, flatfish and codfish. The hatching rate of these eggs in the laboratory is increased considerably when the eggs are cultivated in a bacteria-free medium. Direct microscopic examination, by phase microscopy, of marine fish eggs collected from their natural habitat revealed the presence of large numbers of bacteria and other micro-organisms attached to the egg shell surfaces.

In view of the recently obtained evidence of the prevalence of diseases among marine fish, and drawing upon our knowledge of the importance of diseases among fresh-water fish, we may speculate upon the significance of such diseases among marine fish.

It is reasonable to say that up to the present there has been found no comprehensive analysis of the term " natural mortality " in the population equations which have been prepared for natural stocks. The term has, in fact, been chiefly an item introduced by deduction into an arithmetic operation. Much attention has been paid to the measurement of the amount of mortality, but little work has been done on its causes, and that which has been done has related chiefly to the egg and larval stages. Thus, Dannevig (1940) suggested that certain physical effects of storms might be lethal to eggs ; Sette (1943) and others have written of the effects of currents in carrying eggs and larvae into situations unfavorable in respect of salinity, temperature, or food supply ; Ricker and Foerster (1948) have discussed the nature of mortality among the juvenile stages of sockeye and have suggested that under-nourishment might be a potent factor; Herrington (1948) also discussed types of mortality but seemed to place more emphasis on starvation mortality than was acceptable to some workers (e. g. Kesteven, 1950) . The possibility of non-predator types of mortality has been recognized, but neither the nature nor intensity of these has been systematically treated.

There is also the case of the severe mortality which broke out among commercial species of sponge in the Bahamas late in 1938 (Galtsoff *et al.*, 1939). This mortality appeared to be caused by a fungoid micro-organism, and similar mortalities were reported later off Tarpon Springs, Florida, the southern coast of Cuba, and the coast of British Honduras (Smith, 1939). One species of sponge in the Bahamas, called the "Velvet" sponge, was so severely affected that to the knowledge of one of the team which investigated the 1938 mortality (H.H.Brown), no living specimen has been found in the waters of the Bahamas since 1939. It is possible, therefore, that this is an example of the complete extinction of a species; Professor C.M. Yonge commented in this sense in an article in *Nature*.

A classification of causes of mortality in natural fish population would propose six principal categories of directly operating factors, namely:

1. predators
2. parasites
3. pathogens
4. lethal genes
5. food deficiency
6. physical and chemical factors at lethal values, which at times are of biotic origin.

In addition, any one of these could alone, or in combination with others, render the fish vulnerable to other factors, and, in particular, the intensity of predation might be increased by one or more of the other factors. Of possibly even greater significance is the relation of intensity (of the effect of these factors) with population density, and the speed with which a change in density is followed by a corresponding change in intensity of mortality effect. Since each upswing of population carries a potential for still greater increases, the controlling factors must contain a similar potential for geometric increase of their force. This conclusion is derived from the evidence that natural populations generally maintain a kind of balance whilst at the same time oscillating about the balance level; but the evidence on the amplitude, speed and rhythm of oscillations in some populations suggests, on the one hand, that there must be intricate interactions between the controlling factors, and, on the other, that their sum effect must be closely density dependent. Of the categories above we have doubts about food deficiency as a direct factor although doubtless it could be a predisposing one; physical and chemical factors would seem, except in special circumstances, to be independent of population density; we know nothing of lethal genes in natural fish populations, and we think that predators could not respond sufficiently quickly; for these reasons we are disposed to believe that the principal control responsibility must rest with parasites and pathogens, and most with the latter in view of their more rapid reproduction and presumably easier dispersion.

The value of the foregoing argument would be somewhat lessened if it should be shown that success of spawning and survival of eggs and larvae, and thence brood strength, were entirely fortuitously determined by density independent factors, and that once the brood strength was determined it gradually receded down the mortality curve at a rate "normal" for the population as a whole. However, we do not know of any evidence, among the data on fish population fluctuations, of a freedom and amplitude of oscillation such as would inevitably manifest itself if this were the mechanism. In contrast, there is steadily accumulating evidence of epidemic mortalities of massive proportions (e. g. Gunter, Smith and Williams, 1947). For some of these it has been established with a fair degree of certainty that they were caused by toxic effects of "red water" (Galtsoff, 1949; Smith, 1947; Allen, 1946) and similar phenomena; but in other cases where the cause remains undisclosed (Oppenheimer, 1953), it seems reasonable to believe that it might have been disease.

The recent work on diseases among marine fish will be seen to have, against this background, a very great, potential significance. At the present stage of fisheries biology the main task is to develop an accurate description of the natural systems from which we draw our commercial catches. And in these systems the force of natural mortality is of great importance. If the study of these diseases could contribute to an analysis of the incidence and the intensity of natural mortality it would greatly help the fisheries biologist in describing the dynamics of these systems and in evolving systems for prediction of their behavior. It is unnecessary, at this stage, to speculate upon the contribution which might make for the control of such diseases in some later stage when man's intervention in such natural systems might become more effective than it is at present.

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657

657

4. BEACH AND NEARSHORE PROCESSES ALONG THE SOUTHERN CALIFORNIA COAST *

By Douglas L. Inman †

Erosional and depositional nearshore processes have played an important role in determining the configuration of the southern California coastline. Erosion is usually dominant off headlands and along coastal sections backed by cliffs of alluvium and other unconsolidated material, whereas deposition is most common along indentations between headlands. The over-all effect of such processes is usually a straightening and smoothing of the coastline. However, this is not always the case; differential wave erosion may cause more rapid erosion of material between headlands and thus cause irregularities in the coastline.

The predominance of deposition or erosion in any particular place depends upon a number of interrelated factors such as the amount of available beach sand and the location of its source, the configuration of the coastline and of the adjoining ocean floor, and the effects of wave, current, and tidal action (fig. 1). The establishment and persistence of natural sand beaches and related phenomena are often the result of a delicate balance among a number of these factors, and any changes, natural or man-made, tend to upset this equilibrium.

Source of Beach Sediment. The principal sources of beach and nearshore sediment along the southern California coast are the streams which periodically bring large quantities of sand directly to the ocean, and the sea cliffs of unconsolidated material which are being eroded by waves. In some isolated instances sediment may be supplied by erosion of older unconsolidated deposits in shallow offshore areas. Shepard and Grant (1947) found that the wave erosion of rocky coasts in southern California has been negligible during the past 50 years, even where the rocks were relatively soft shales. On the other hand, they found a retreat of as much as a foot a year in unconsolidated formations.

Streams, however, are by far the most important source of sand. The shoreline at the mouth of the Santa Clara River, near the city of Ventura, advanced 300 feet between 1933 and 1938 principally as a result of deposition during the 1938 flood. The Corps of Engineers (1952) estimate that the average rate of littoral drift of sand from the Santa Clara River delta, toward Port Hueneme to the southeast, was about 800,000 cubic yards a year. The combination of abundant local source of sand and protection from wave erosion by the Channel Islands and Point Conception has resulted in building the shoreline along this section of coast well seaward of the adjacent headlands of Ventura and Point Mugu.

Beaches do not always have local sources of sand, but may receive sand from other beaches many miles away. For example, there is evidence (Trask, 1952) that the beaches near Santa Barbara, where the average littoral drift is about 280,000 cubic yards a year, may receive some sand from beaches north of Point Conception. Also, studies of the beaches in the Santa Monica area suggest that some of the sand there is derived from sources northwest of Point Dume and possibly from northwest of Point Mugu (Handin, 1951, p. 42).

Southern California beaches are generally narrow and backed by sea cliffs except where deposition has caused the beaches to build seaward. Examples of wide beaches are found near the Santa Clara River, along portions of Santa Monica Bay, at Newport Beach, and at Mission and Silverstrand Beaches near San Diego. The beach material consists predominantly of well sorted medium to fine sand, interrupted here and there by pebble and cobble foreshores. The coarsest material is commonly found on pocket beaches near rocky headlands, as at Point Mugu and Point La Jolla. The composition of the beach sands is mostly quartz with minor amounts of the feldspars and heavy minerals. The heavy minerals (i.e., those with a specific gravity greater than about 2.85) generally comprise between 1 and 15 percent of the total sample, and are most abundant in the finer size fractions. The most common heavy minerals are hornblende, augite, epidote, magnetite, ilmenite, apatite, garnet, sphene, and zircon (Handin, 1951; Inman, 1950b, 1953; Trask, 1952). Biotite is common in the stream sands and offshore sediments, but because it is easily retained in suspension, is usually rare in the beach sands.

Waves. Waves and the currents which they generate are perhaps the single most important factor in the transportation and deposition of nearshore sediments. Waves are effective in moving material along the bottom, in placing it in suspension for weaker currents to transport, and, in the absence of beaches, waves erode cliffs and sea walls directly by the force of their breaking. The deciding factors in determining the effect of waves on the coastline, and the direction of the wave-generated longshore currents which move material along the coast are: (1) the direction of approach of the waves, (2) the wave characteristics, such as height and length, and (3) the configuration of the sea floor.

Wave action along the southern California coast is seasonal in nature, in response to the changing wind systems over the Pacific Ocean where the waves are generated. Important meteorological con-

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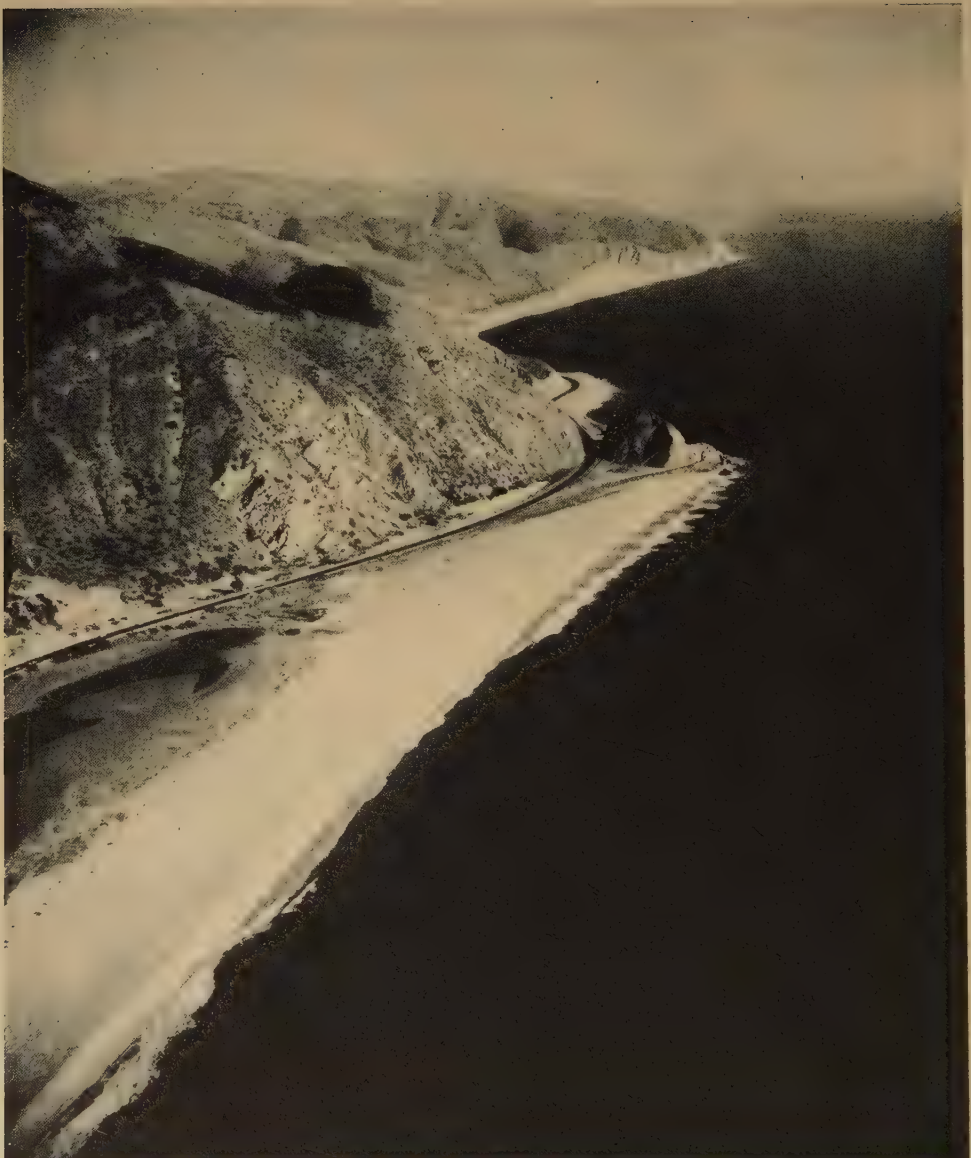

FIGURE 1. The effect of headlands on the accretion of beach sand is shown in this photograph of Point Mugu, California (view southeast). The point forms a natural obstruction which interrupts the littoral drift of sand, causing accretion and a wide beach to form on the up-current side (foreground), and cliff erosion with occasional pocket beaches in the current lee where the supply of sand is diminished. *Photo courtesy Department of Engineering, University of California, Berkeley.*

ditions resulting in high waves along the coast are local storms, coastal fronts, and storms in the Gulf of Alaska. These waves occur mostly during the winter and spring and occasionally in the fall, and approach the coast principally from the northwest and west (Scripps Institution of Oceanography, 1947). During the summer months the waves are characteristically much lower in height and approach the coast from the west and south-southwest. The most southerly of these waves, sometimes called "southern swell," are generated during our summers by winter storms in the southern hemisphere and may travel more than 5,000 miles before breaking on the shore of southern California.

The profiles of ocean swell in deep water are long and low, approaching a sinusoidal form. However, as waves enter shallow water the wave velocity and length decrease, the wave steepens and the wave height increases until the wave train consists of peaked crests separated by flat troughs. Near the breaker zone the process of steepening is accelerated so that the breaking wave may attain a height several times greater than the deep-water wave. This transformation is particularly pronounced for long-period swell from a distant storm. The profiles of local storm waves show considerable steepness even in deep water, so that the shallow-water steepening is not as pronounced as in the case of ocean swell (Munk and Taylor, 1947).

The shallow-water transformation of waves commences at the depth where the waves feel bottom. This depth is equal to one-half the deep-water wave length, where the wave length is the horizontal distance from wave crest to crest. The deep-water wave length in feet is given by the relationship $L = 5.12T^2$, where T is the wave period in seconds. Upon entering shallow water waves are also subjected to refraction, a process in which the wave crests tend to parallel the depth contours. For straight coasts with parallel contours, this decreases the angle between the approaching wave and the coast, and causes a spreading of the energy along the crests. The wave height is decreased by this process, but the effect is uniform along the coast. A submarine canyon or depression causes waves to be refracted or bent in such a manner that waves over the canyon will diverge, causing the waves to decrease in height and the line of wave crests to be convex toward the shore. Waves will converge on either side of the canyon or over a ridge, causing the wave height to increase and the line of wave crests to be concave toward the shore. The amount of wave refraction and consequent change in wave height and direction at any point along the coast is a function of wave period, direction of approach, and the configuration of the bottom topography.

Waves from distant storms, such as southern swell, may have periods as great as 20 seconds or more when they reach the southern California coast. Since refraction commences when waves reach a depth equal to one-half the wave length, waves with periods of 20 seconds will feel bottom and be refracted by topographic features on the ocean floor in depths as great as 1000 feet. Thus the formation of beaches and the effect of waves on a coastline may be influenced by the topography of the bottom many miles from the coast. The concentration of wave energy at points along the coast by submarine ridges often results in severe erosion and damage to coastal structures. Damage from this cause occurs periodically along the California coast when the wave period, deep-water direction of approach, and height are such as to focus energy on coastal structures (Horrer, 1950; Inman, 1950a).

Currents. When waves break so that there is an angle between the crest of the breaking wave and the beach, the momentum of the breaking wave has a component along the beach in the direction of wave propagation. This results in the generation of longshore currents that flow parallel to the beach inside of the breaker zone (fig. 2). These currents are largely responsible for the littoral drift of beach material. After flowing parallel to the beach as longshore currents, the water is returned seaward along relatively narrow zones by rip currents. The net onshore transport of water by wave action in the breaker zone, the lateral transport inside of the breaker zone by longshore currents, and the seaward return of the flow through the surf zone by rip currents constitute a near-shore circulation system. The pattern that results from this circulation commonly takes the form of an eddy or cell with a vertical axis.

In many cases where waves break along a straight beach with parallel bottom contours, it is possible to predict the velocity of the longshore current from a consideration of wave and beach characteristics (Inman and Quinn, 1952). However, where the beaches are not straight, or where offshore topography causes differential wave refraction, the longshore currents are dependent on the gradient of breaker height along the beach as well as on the angle between the breaking wave and the beach. For such cases, the positions of the circulation cells are largely dependent upon the location of zones of wave convergence and divergence, and quantitative prediction of longshore velocity cannot be made (Shepard and Inman, 1951a).

Points, breakwaters, and piers all influence the circulation pattern and alter the direction of the currents flowing along the shore. In general these obstructions determine the position of one side of the circulation cell. In places where relatively straight beaches are terminated on the down-current side by points or other obstructions, a pronounced rip current extends seaward. During periods of large waves having strong diagonal approach these rips can be traced seaward for one or more miles.

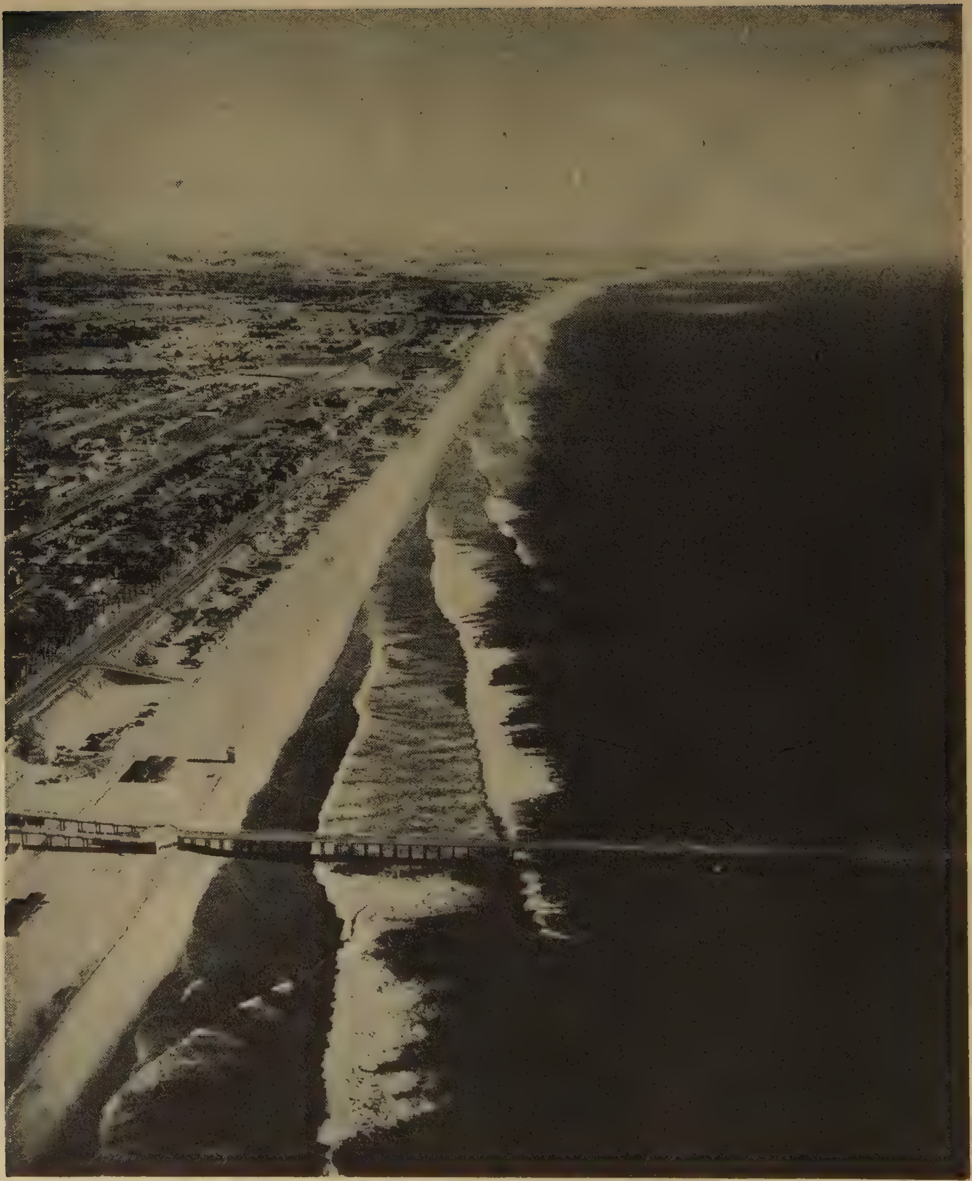

FIGURE 2. Longshore currents are generated when waves approach the beach at an angle. Such currents flow parallel to the beach and result in a littoral drift of sand along the beach. In this photograph of Oceanside, California, the longshore current is flowing towards the observer. *Photo courtesy Department of Engineering, University of California, Berkeley.*

Longshore currents are largely responsible for the littoral drift of beach material along the coast. Although there are local and temporary reversals of current direction, the net sand transport along most southern California beaches is from the northwest toward the southeast. Obstructions—natural or man-made—in the path of these currents often have profound effects upon the beaches in the neighboring areas. Usually the beaches build seaward up-current from obstructions and are eroded in the current lee, where the supply of sand is diminished (fig. 1). Numerous examples of the effectiveness of coastal structures in interrupting the littoral drift of beach material are found along the California coast, particularly where breakwaters and jetties have been constructed as at Santa Barbara, Port Hueneme, Santa Monica, and Redondo Beach. The rate of accretion of sand behind such structures has provided the most reliable information about the rate of littoral drift of sand along the coast.

Mechanics of Beach Formation. Waves are effective in causing sand to be transported laterally along the beach by longshore currents, and in causing movements of sand from the beach foreshore to deeper water and back again to the foreshore. Along the southern California coast the migration of sand between the beaches and deeper water is seasonal, in response to the changes in wave height, period, and direction of approach. In general, the beaches build seaward during the small waves of summer and are cut back by high winter storm waves (Shepard and La Fond, 1940; Shepard, 1950). There are shorter cycles of cut and fill associated with spring and neap tides, and with non-seasonal waves and storms. Bottom surveys indicate that most offshore-onshore interchange of sand occurs in depths less than 30 feet, but that some effects may extend to greater depths (Shepard and Inman, 1951b).

The mechanics of transportation of beach and nearshore material are not clearly understood. However, there has been much research on the problem, and a summary of available concepts based partly on theory and partly on observations is given in the following discussion (also, see Eaton, 1951).

As mentioned in the discussion of longshore currents, there is a shoreward mass transport of water associated with wave motion near the breaker zone. This shoreward transport of water can apparently be interpreted as resulting in a rise in the sea surface near shore. The piling up of water must be compensated by a seaward return flow, part of which is in the form of rip currents. Application of solitary wave theory to the surf zone (Munk, 1949a), supported by field observations (Inman and Quinn, 1952), suggests that the shoreward mass transport of water is a maximum at the water surface and that, in addition to rip currents, this transport is compensated by a net seaward return flow along the bottom. The magnitude of net offshore drift along the bottom (as determined from averages over straight beaches three-quarters of a mile long and for periods of one hour) usually does not exceed three-tenths of a foot per second.

The instantaneous particle motion associated with shallow-water progressive waves is oscillatory in nature, the motion under the crest being in the direction of wave propagation, while that under the wave trough is in the opposite direction. As waves near the breaker zone, a differential develops between the magnitude of the crest and trough orbital velocities; the velocity under the crest exceeds that of the trough and becomes of shorter duration. In general, the differential between crest and trough orbital velocities increases as the wave height and frequency decrease. However, the picture of wave motion in shallow water is considerably complicated by currents and by longer-period waves or surges which in some cases may result from the alternation of groups of high and low waves in the surf zone (Munk, 1949b; Williams and Isaacs, 1952).

The relative increase in the onshore velocity under the wave crest as compared with the offshore velocity of the wave trough probably accounts for the shoreward migration of sand during periods of low waves, particularly when the waves have long periods. On the other hand, a greater amount of material is maintained in suspension above the bottom when the waves are high and have short periods, and for this condition, the differential between onshore and offshore orbital velocities is much less. Thus the net offshore drift along the bottom may result in a net offshore transport of material when the waves are high and have short periods. It is also possible that a net transport of sediment could exist in the absence of a net current if a horizontal gradient were to develop in the concentration of suspended material. Such a gradient does exist near the surf zone (Beach Erosion Board, 1933), where the concentration of suspended material is greater in the zone of breaking waves than it is seaward, and may result in an offshore transportation by diffusion.

High waves also augment beach erosion by increasing the velocity of the currents in the nearshore circulation system. Sand is transported laterally along the beach by longshore currents and through the breaker zone to deeper water by rip currents.

Grant (1948) points out that the mechanics of accretion and erosion of the beach foreshore appear to be connected with the height of the water table in the beach, which in turn is related to waves and tides. Percolation of the uprush into a dry beach reduces the amount of flow in the backwash and is thus conducive to deposition of the sand transported by the uprush. Large waves elevate the water table in the beach. When the beach is saturated the backwash has a higher velocity which enhances erosion of the foreshore.

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(Publication delayed.)

ON THE DIFFUSION OF TIDES INTO PERMEABLE ROCK

BY

G. F. CARRIER AND W. H. MUNK[1]

1. Introduction. In the irrigation wells of the Hawaiian Islands, water-level fluctuations whose frequency components correspond to those of the ocean tides have been observed by Cox [1]. In this paper we shall formulate the problem associated with this phenomenon, assuming the observed ground-water fluctuations to represent a diffusive transmission of the tidal disturbances through the porous volcanic structure of the island. The agreement with observation is fair. The results obtained here may find application in a method for estimating subsurface permeability.

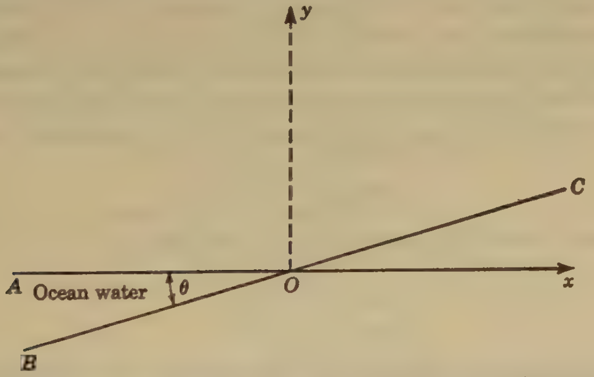

FIG. 1. Below BOC the medium is permeable. The pressure variations on OB depend only on the tidal water-level variations (mean water level: OA).

2. The Formulation of the Problem. Consider the situation in Fig. 1. If the ocean level remained fixed, the pressure distribution in the fluid would be

$$p_0(y) = -\rho_0 g y. \tag{1}$$

However, when the fluid is in motion, the pressure distribution depends on the velocity field. Within the porous medium, we adopt Darcy's law

$$\mathbf{v} = \frac{\mathbf{m}}{\rho_0} = -\frac{k}{\mu}\,\text{grad}\,(p - p_0), \tag{2}$$

where p is the pressure, k the permeability of the medium (taken as isotropic and constant), μ the viscosity of the fluid, $\mathbf{m}$ the mass flow per unit area, ρ_0 the mean fluid density, and $\mathbf{v}$ as defined by $\mathbf{m}/\rho_0$ is the "velocity."

Equation (2) replaces the law of conservation of momentum but we must also invoke the mass-conservation law. This takes the form

$$\text{div}\,\mathbf{m} = -\frac{\partial}{\partial t} A\rho \tag{3}$$

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[1] Contribution from the Scripps Institution of Oceanography, new series, 659.

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where A is that fraction of the volume which is filled with fluid (*i.e.*, the porosity). We adopt a simple compressibility law for the rock and fluid, *viz.*,

$$\rho A = \rho_0 A_0[1 + \gamma(p - p_0)], \tag{4}$$

where γ is essentially $(\rho_0 c^2)^{-1}$ with c the speed of sound in the fluid. We may now combine the foregoing equations to obtain

$$\Delta q = \frac{\mu\gamma A_0}{k} q_t, \tag{5}$$

where $q = p - p_0$ and Δ is the Laplace operator.

In equation (5) the expression $k/\mu\gamma A_0$ has the dimensions of diffusivity (square centimeters per second), and the equation is of the diffusion type rather than a wave equation. The essential reason for this is that the pressure gradient is proportional to a velocity rather than to an acceleration.

The boundary conditions must now be given. On OB, the sea bottom, we may associate the "pressure" q with the tidal-wave amplitude. In fact, if we decide to consider a single periodic tidal-wave contribution, we write

$$q_{(\text{on } OB)} = q_1 e^{i\omega t}.$$

On the free surface near Ox, we have from equation (2)

$$\eta_t = \frac{\mathbf{j} \cdot \mathbf{v}}{A} = \frac{k}{\mu A} q_y, \tag{6}$$

where $\eta(x,t)$ is the y-coordinate of the free surface. On this surface, however, $p = 0$, and using equation (1),

$$q(x,\eta) = -p_0 = \rho_0 g \eta. \tag{7}$$

We may now use equations (6) and (7) to obtain

$$q_t = -\frac{\rho_0 g k}{\mu A} q_y. \tag{8}$$

In these equations, q should be evaluated at $y = \eta$ but, in the usual linearized way, we apply equation (8) at $y = 0$.

It is now convenient to define some dimensionless quantities, *viz.*:

$$\tau = \omega t, \quad y\frac{\mu A \omega}{\rho_0 g k} = \frac{y}{L} = y', \qquad \frac{x}{L} = x',$$

$$\epsilon = \frac{\rho_0^2 g^2 k \gamma}{\mu A_0 \omega}.$$

We then have

$$q_{x'x'} + q_{y'y'} = \epsilon q_\tau, \tag{9}$$

$$q(OB) = e^{i\tau}, \tag{10}$$

$$q_\tau(x',0,\tau) + q_{y'}(x',0,\tau) = 0. \tag{11}$$

If we now omit the prime on x and y and consider the periodic response of the system, we may write

$$q(x,y,t) = \varphi(x,y)e^{i\tau}$$

and equations (9) to (11) become

$$\Delta\varphi - i\epsilon\varphi = 0, \tag{12}$$

$$\varphi = 1 \text{ on } OB, \tag{13}$$

$$\varphi_y(x,0) + i\varphi(x,0) = 0, \qquad (x > 0). \tag{14}$$

This problem will be solved for two orientations of the line OB: (1) when the ocean-land interface is a vertical cliff ($\theta = 90°$); (2) when OB is horizontal ($\theta = 0°$). The latter case is the more realistic one since the bottom slope seldom exceeds 5 to 10°.

3. The Horizontal Interface. In this problem, equation (13) takes the form

$$\varphi(x,0) = 1, \qquad (x < 0). \tag{15}$$

It is convenient to introduce the Fourier transform of φ and, in fact, we shall find φ by invoking the Wiener-Hopf technique. We define

$$\bar{\varphi}(\xi,y) = \int_{-\infty}^{\infty} \varphi(x,y)e^{-i\xi x}\,dx, \tag{16}$$

and the transform of equation (12) becomes

$$\bar{\varphi}_{yy} - (\xi^2 + i\epsilon)\bar{\varphi} = 0. \tag{17}$$

Hence

$$\bar{\varphi} = A(\xi)e^{y\sqrt{\xi^2+i\epsilon}}. \tag{18}$$

Now we can define $h_1(x)$ and $h_2(x)$ by

$$h_1(x) = \lim_{a\to 0}\begin{cases} e^{ax}, & (x < 0), \\ 0, & (x > 0), \end{cases}$$

$$h_2(x) = \begin{cases} 0, & (x < 0), \\ ?, & (x > 0), \end{cases}$$

and $h_1(x) + h_2(x) = \varphi(x,0)$. However,

$$A(\xi) = \bar{\varphi}(\xi,0) = \bar{h}_1(\xi) + \bar{h}_2(\xi).$$

It can be ascertained that

$$\bar{h}_1(\xi) = \frac{1}{a - i\xi} \tag{19}$$

and that $\bar{h}_2(\xi)$, being the transform of a function which vanishes for $x < 0$, is regular in ξ whenever $\text{Im}(\xi) < \delta$, where δ is a nonnegative real number. We can now define

$$f(x) = \varphi_y(x,0) + i\varphi(x,0)$$

and

$$\begin{aligned} \bar{f}(\xi) &= (\sqrt{\xi^2 + i\epsilon} + i)A(\xi) \\ &= (\sqrt{\xi^2 + i\epsilon} + i)[\bar{h}_1(\xi) + \bar{h}_2(\xi)]. \end{aligned} \tag{20}$$

Because of our boundary conditions, $\bar{f}$ (like $h_1(\xi)$) is analytic in the upper half ξ-plane. We can anticipate, in fact, that each function of ξ appearing in equation (20) will be regular in a horizontal strip lying below $i(\epsilon/2)^{\frac{1}{2}}$ and above the smaller of $-i(\epsilon/2)^{\frac{1}{2}}$ and $-ia$. In this strip, then, equation (20) is a meaningful equation. We now anticipate that $G(\xi) = \sqrt{\xi^2 + i\epsilon} + i$ can be written

$$G(\xi) = G_+(\xi)G_-(\xi),$$

where $G_+(\xi)$ is analytic and has no zeros above $\xi = -i(\epsilon/2)^{\frac{1}{2}}$ and where $G_-(\xi)$ has the same properties below $\xi = i(\epsilon/2)^{\frac{1}{2}}$. We can write equation (20) in the form

$$\text{(21)} \qquad \frac{\bar{f}(\xi)}{G_+(\xi)} - G_-(-ia)\overline{h_1}(\xi) = \overline{h_2}(\xi)G_-(\xi) + [G_-(\xi) - G_-(-ia)]\overline{h_1}(\xi).$$

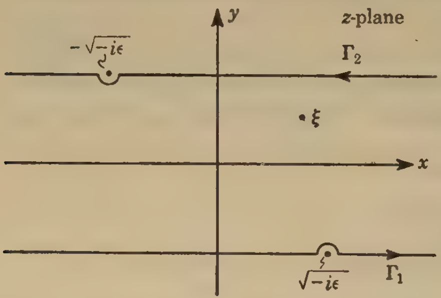

FIG. 2. Integration contour for equation (23).

The left side is analytic in the upper halt plane, the right side in the lower, and, by the usual analytic-continuation arguments, we may associate each side with an entire function. Since, as $\xi \to \infty$, both $\overline{h_1}(\xi) \to 0$ and $1/G_+(\xi) \to 0$, and since $\bar{f}(\xi)$ should be bounded at ∞, this entire function must be identically zero. Thus,

$$\overline{h_2}(\xi) = \left[\frac{G_-(-ia)}{G_-(\xi)} - 1\right]\overline{h_1}(\xi).$$

The free-surface level[2] is then given by

$$\text{(22)} \qquad h_2(x) = \frac{i}{2\pi}\int_{-\infty}^{\infty} \xi^{-1}\left[\frac{G_-(0)}{G_-(\xi)} - 1\right] e^{i\xi x}\, d\xi,$$

when we go to the limit $a = 0$. We cannot evaluate this, of course, until we find $G_-(\xi)$.

4. The Factorization of $G(\xi)$. We shall use a well-known technique [2] to obtain $G_-(\xi)/G_-(0)$. We note that

$$\text{(23)} \qquad \ln G(\xi) = \ln G_+(\xi) + \ln G_-(\xi) = \frac{1}{2\pi i}\int_\Gamma \frac{\ln G(z)}{z - \xi}\, dz$$

for all points in Γ, provided $\Gamma = \Gamma_1 + \Gamma_2$ is as indicated in Fig. 2. We may now define G_+ to be that contribution of equation (23) associated with Γ_1 and G_- to be that associated with Γ_2. It is clear that the appropriate analytic continuations of these functions into their respective half planes of definition are automatic. We want to compute, then,

$$H(\xi) = \ln G_-(\xi) = -\frac{1}{2\pi i}\int_{-\infty + i\sqrt{\xi/2}}^{+\infty + i\sqrt{\xi/2}} \ln [G(z)](z - \xi)^{-1}\, dz,$$

---

[2] Corresponding to unit tidal amplitude.

and, for Im $\xi < 0$, we may write

$$H(\xi) = -\frac{1}{2\pi i}\int_{-\infty}^{\infty} \ln\,[(z^2 + i\epsilon)^{\frac{1}{2}} + i](z - \xi)^{-1}\,dz. \tag{24}$$

If we differentiate once with regard to ξ and integrate by parts, we obtain a readily integrable formula for $H'(\xi)$. In fact, the result is

$$H'(z) = \frac{1}{2(z - i\beta)} + \frac{1}{2(z^2 + \beta^2)}\left[\beta \ln \frac{\beta + 1}{\beta - 1} - \frac{z}{(z^2 + \alpha^2)^{\frac{1}{2}}} \ln \frac{z + (z^2 + \alpha^2)^{\frac{1}{2}}}{z - (z^2 + \alpha^2)^{\frac{1}{2}}}\right], \tag{25}$$

where the branches must be chosen so that G'_- is regular in the lower half plane. In this formula $\alpha^2 = i\epsilon$, $\beta^2 = 1 + i\epsilon$. In the limit $\epsilon \to 0$, we have

$$H'(\xi) \to +\frac{1}{2}(\xi - i)^{-1} - \frac{1}{\pi}\frac{\ln i\xi}{\xi^2 + 1}. \tag{26}$$

The quantity $G_-(0)/G_-(\xi)$ is defined by

$$\frac{G_-(0)}{G_-(\xi)} = -\int_0^\xi H'(z)\,dz, \tag{27}$$

where H' is given by equation (25) for the compressible situation and by equation (26) for the incompressible case. Equation (22) now yields

$$h_2(x) = \frac{i}{2\pi}\int_{-\infty}^{\infty} \xi^{-1}\left[\exp\left(-\int_0^\xi H'(z)\,dz + i\xi x\right) - 1\right]d\xi. \tag{28}$$

The evaluation of this integral will be discussed in Sec. 6.

5. The Vertical-cliff Problem. If we now consider the situation where the land-ocean interface is vertical, one must find the solution of

$$\Delta\varphi = i\epsilon\varphi, \qquad (\text{in } x > 0, y < 0). \tag{29}$$

$$\varphi(0,y) = 1, \qquad (y < 0). \tag{30}$$

$$\varphi_y(x,0) + i\varphi(x,0) = 0, \qquad (x > 0). \tag{31}$$

It is convenient to define $\psi(x,y) = \varphi_y + i\varphi$. The function ψ must always obey equation (29), and the boundary conditions on ψ become

$$\psi(0,y) = i, \qquad (y < 0), \tag{32}$$

and

$$\psi(x,0) = 0, \qquad (y > 0). \tag{33}$$

We can now extend the domain on which ψ is defined to the entire right half plane and replace the present problem by that of finding $\psi(x,y)$, which obeys (15) and the condition

$$\psi(0,y) = \begin{cases} i = \lim\limits_{a\to 0} ie^{ay}, & (y < 0), \\ -i = \lim\limits_{a\to 0} -\,ie^{-ay}, & (y > 0). \end{cases} \tag{34}$$

Since ψ will be odd in y, equation (33) will be automatically satisfied. The solution is now most readily obtained by using Fourier transforms again. We define $\bar{\psi}(x,\eta) = \int_{-\infty}^{\infty} \psi(x,y)e^{-i\eta y}\,dy$. Multiplying equation (29) by $e^{-i\eta y}$ and integrating yields

$$\bar{\psi}_{xx} - (\eta^2 + i\epsilon)\bar{\psi} = 0$$

so that

$$\bar{\psi} = A(\eta)\exp\left(-\sqrt{\eta^2 + i\epsilon}\,x\right).$$

The function A must be obtained from the boundary conditions, *i.e.*,

$$A = \bar{\psi}(0,\eta) = -2\eta(\eta^2 + a^2)^{-1}.$$

Finally, since $\bar{\psi} = i(\eta + 1)\bar{\varphi}$, we have

$$\varphi = \frac{1}{2\pi}\int_{-\infty}^{\infty} \bar{\varphi}e^{i\eta y}\,d\eta = \frac{i}{2\pi}\int_{-\infty}^{\infty} \frac{2\eta\exp\left(i\eta y - \sqrt{\eta^2 + i\epsilon}\,x\right)}{(\eta^2 + a^2)(\eta + 1)}\,d\eta. \tag{35}$$

In particular, on $y = 0$, we have

$$\begin{aligned}\phi(x,0) &= \exp(-\beta x) - \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{ze^{ixz}}{\sqrt{z^2 + \alpha^2}(z^2 + \alpha^2 + 1)}\,dz \\ &= \exp(-\beta x) + \frac{2i}{\pi}\left\{\left(\operatorname{arcsinh}\frac{1}{\alpha}\right)\sinh\beta x \right. \\ &\qquad \left. - \int_0^x \cosh[\beta(x - \tau)]K_0(\alpha\tau)\,d\tau\right\},\end{aligned} \tag{36}$$

where K_0 is the modified Hankel function and $\beta = (1 + i\epsilon)^{\frac{1}{2}}$. Finally, in the limit $\epsilon \rightarrow 0$, we note that

$$\operatorname{arcsinh}\frac{1}{\alpha} \sim \ln(2\epsilon^{-\frac{1}{2}}) - \frac{i\pi}{4}$$

and

$$K_0(\alpha,\tau) \sim -\ln\frac{\alpha}{2} - \gamma - \ln\tau.$$

Thus, for $\epsilon \rightarrow 0$,

$$\varphi(x,0) = e^{-x} + \frac{2i}{\pi}\int_0^x (\gamma + \ln\tau)\cosh(x - \tau)\,d\tau,$$

where γ is Euler's constant. This function, $\varphi(x,0)$, behaves asymptotically like $-2i/\pi x$.

6. The Results. We shall reduce the integral implied by equations (26) and (28) and those given by equation (36) to a form convenient for computation. For the horizontal-interface problem with $\alpha = 0$ (the incompressible case)

$$\begin{aligned}\varphi(x,0) &= \frac{i}{2\pi}\int_{-\infty}^{\infty} \frac{\left[\exp\left\{\pi^{-1}\int_0^{\xi}[\ln iz/(z^2 + 1)]\,dz + i\xi x\right\} - 1\right]dz}{\sqrt{1 + i\xi}} \\ &= 2^{-\frac{1}{2}}e^{-x-i\pi/8} + \pi^{-1}e^{-5\pi i/8}\int_0^1 \frac{e^{-xy} - y^{-\frac{1}{2}}e^{-x/y}}{(1 + y)^{\frac{1}{2}}(1 - y)}\cos u\,dy \\ &\qquad - \pi^{-1}e^{-i\pi/8}\int_0^1 \frac{e^{-xy} + y^{-\frac{1}{2}}e^{-x/y}}{(1 + y)^{\frac{1}{2}}(1 - y)}\sin u\,dy,\end{aligned} \tag{37}$$

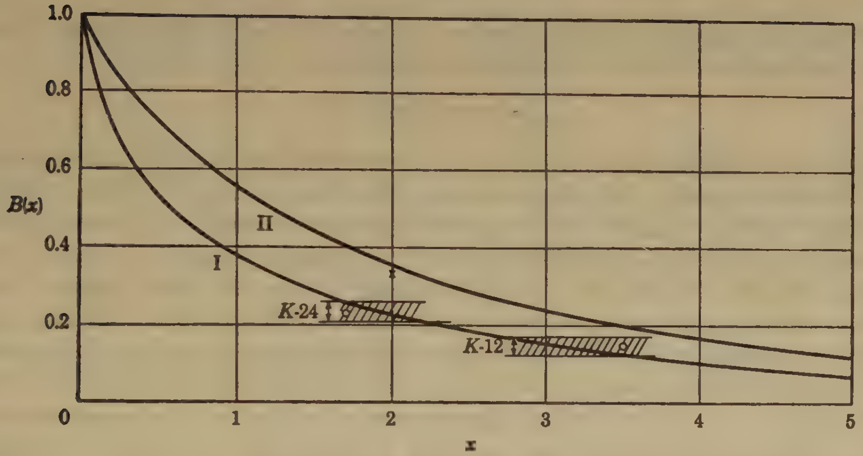

Fig. 3. Ground-water amplitude vs. distance inland. Curve I, incompressible horizontal interface. Curve II, incompressible vertical interface. x, $\epsilon = 0.01$ (vertical interface). ○, average of observed amplitudes. K-12, 12-hr. tide observation range at Kuau. K-24, 24-hr. tide observation range at Kuau.

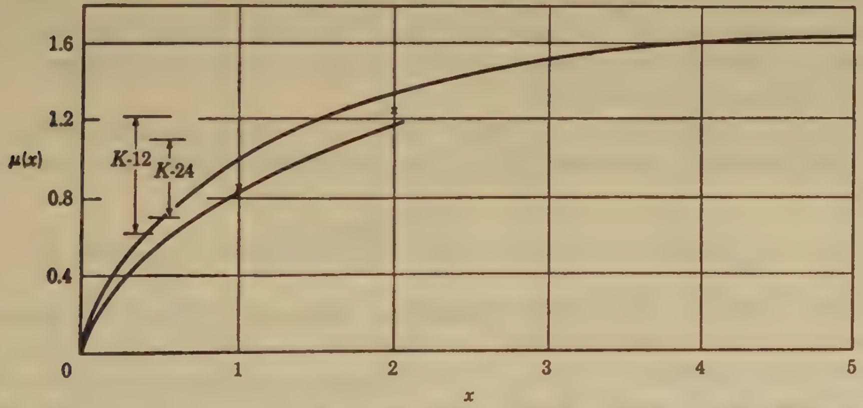

Fig. 4. Ground-water phase lag vs. distance inland. Curve I, incompressible horizontal interface. Curve II, incompressible vertical interface. x, $\epsilon = 0.01$ (vertical interface). K-12, 12-hr. tide observation range at well. K-24, 24-hr. tide observation range at well.

where $u = \pi^{-1}\int_v^1 [\ln v/(1 - v^2)]\,dv$. The numerical integration of this latter form yields the results depicted in Figs. 3 and 4.

The vertical-cliff result as given by equation (36) can also be written

$$\varphi(x,0) = e^{-x\sqrt{1+\alpha^2}} - \frac{2i}{\pi}\int_0^1 \frac{e^{-x\sqrt{y^2+\alpha^2}} - e^{-x/\sqrt{y^2+\alpha^2}}}{1 - y^2}\,dy. \tag{38}$$

Asymptotically these functions [*i.e.*, the $\varphi(x,0)$ of equations (37) and (38)] behave like $-i/\pi x$ and $-2i/\pi x$, respectively, for $\alpha = 0$. The results of the numerical integration of this equation are also plotted in Figs. 3 and 4, both for $\epsilon = 0$ and $\epsilon = 0.01$. The notation on these curves is given by

$$\varphi(x,0) = B(x)e^{-i\mu(x)}. \tag{39}$$

The experimental observations which are available are scanty, and the spread of the data is great. The observations at the Kuau well [1] are also indicated in Figs. 3 and 4. Note that the phase-lag observations are not easily interpreted but that the amplitude decay is reasonably consistent. Since, for a given well the "distance" x is proportional to the frequency, the 12- and 24-hr. tides should correspond to x values having the ratio 2. Choosing the location of these data points on this basis, we find that this location is consistent with a permeability value of 5×10^{-6} cm.^{2} and a value of ϵ of order 0.01. This permeability is consistent with other estimated values for this volcanic material. The observed phase lag, however, is much too low to be consistent with our theory. Furthermore, as is indicated by the vertical-cliff computations, the compressibility correction would lead to a greater discrepancy—not a smaller one. Thus, the phase-lag results are somewhat disappointing although the amplitude decay is consistent with our theory. This is not too surprising since the nonhomogeneity of the geologic setup can easily upset the validity of the results. Nevertheless, it is difficult to explain the very low phase-lag observations and especially the fact that this phase lag seems relatively independent of frequency.

Finally, it seems of some interest to record the asymptotic behavior of the function defined by equation (28) for the compressible case. One can show that

$$h_2(x) \approx -\frac{i}{2\pi}\left[K_1(\alpha x) - \int_{\alpha x}^{\infty} K_2(\tau)\,d\tau\right] - \frac{\alpha^2 \ln \alpha}{2\pi^2}\left[K_1'(\alpha x) + K_0(\alpha x)\right] + \cdots,$$

where K_ν is the Hankel function of imaginary argument. However, this series is an asymptotic representation in $1/\alpha$ rather than in x, and the function is well represented only when $x \gg |\ln \alpha|$. That is to say, it is useful only in a range of x where the compressibility is important. Since $|\alpha| = 0(0.1)$ and $x = 0(1)$ in the cases of interest to us, these results are not particularly pertinent to the present problem.

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660

SEPARATE from

GULF OF MEXICO
ITS ORIGIN, WATERS, AND MARINE LIFE

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GULF OF MEXICO FORAMINIFERA

By **Fred B. Phleger** and **Frances L. Parker**,[1] *The Scripps Institution of Oceanography, University of California*

Foraminifera are relatively large, marine Protozoa having either a calcareous or an arenaceous test; they are both benthonic and planktonic in habitat. Their tests contribute a large percentage of the material in marine sediments. Study of Foraminifera has been mostly confined to the occurrence of empty tests in marine sediments, and all identifications are based upon test morphology.

Little is known of Gulf of Mexico Foraminifera except from the Dry Tortugas and from the northwest area. Phleger (1951) and Phleger and Parker (1951) have studied living and dead assemblages from plankton tows and cores taken off shore between Point Isabel and Atchafalaya Bay, and the present report is largely a summary of the pertinent features of that work. These samples were collected from 551 stations spaced in 12 traverses extending from the 10-fathom curve to the center of the Sigsbee Deep. Flint (1899) and Cushman (1918–31) have described material collected by the United States Bureau of Fisheries ship, *Albatross*, from the northern part of the Gulf of Mexico east of the Mississippi Delta. Kornfeld (1931) described some shallow-water and littoral Foraminifera from a few stations between the Mississippi Delta and the International Boundary. Cushman and Bermudez (1945) reported a new species of *Rotalia* from the mouth of the Rio Grande. Cushman (1922) has described numerous species from the shallow-water areas of the Tortugas.

BENTHONIC FORAMINIFERA

The area investigated in the northwest Gulf of Mexico between the Mississippi Delta and the International Boundary is one of clastic sediments. Clastic sediments also occur east of the delta as far as Mobile Bay and along the coast of Mexico. The continental shelf bordering Louisiana and Texas has numerous isolated calcareous reefs. The principal calcareous areas in the region are along the coasts of Florida and Yucatán. The Foraminifera assemblages in these two sedimentary environments are quite distinctive and are treated separately in the following summary. The most extensive sampling and study has been done in the clastic sediments.

Clastic areas.—Figures 55 through 58 list the principal benthonic species found in the northwest Gulf of Mexico; this figure is reproduced from Phleger (1951). The depth range shown for each species is a generalization based upon distributions from samples in all 12 traverses taken. This assemblage is related to the Atlantic assemblage but contains some elements reported only from the Gulf of Mexico.

The benthonic faunas in the northwest Gulf may be grouped into six depth biofacies with boundaries at the following approximate depths: 100 m., 200 m., 600 m., 1,000 m., and 2,000 m. In addition, there are three subfacies in the upper 100 m. of water depth. The boundaries between these biofacies are not sharp but vary through about 10–20 percent of the depth involved. Figure 59 summarizes the depth of biofacies and gives depth ranges of representative species as an illustration of the basis for distinguishing the facies.

The most striking depth biofacies boundary in this area is at about 100 m. This coincides with the depth of the water layer which is affected by changing seasons and therefore shows seasonal temperature ranges, in which the greatest organic production occurs, and which is turbulent, at least in part. Deeper biofacies boundaries may be correlated with the temperature ranges if they occur in the permanent thermocline. The boundary at about 2,000 m. is believed to be due to some environmental factor other than temperature, since there is no significant temperature change

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 660, Contribution No. 16, Marine Foraminifera Laboratory. Work done on Office of Naval Research Project NR 081 050.

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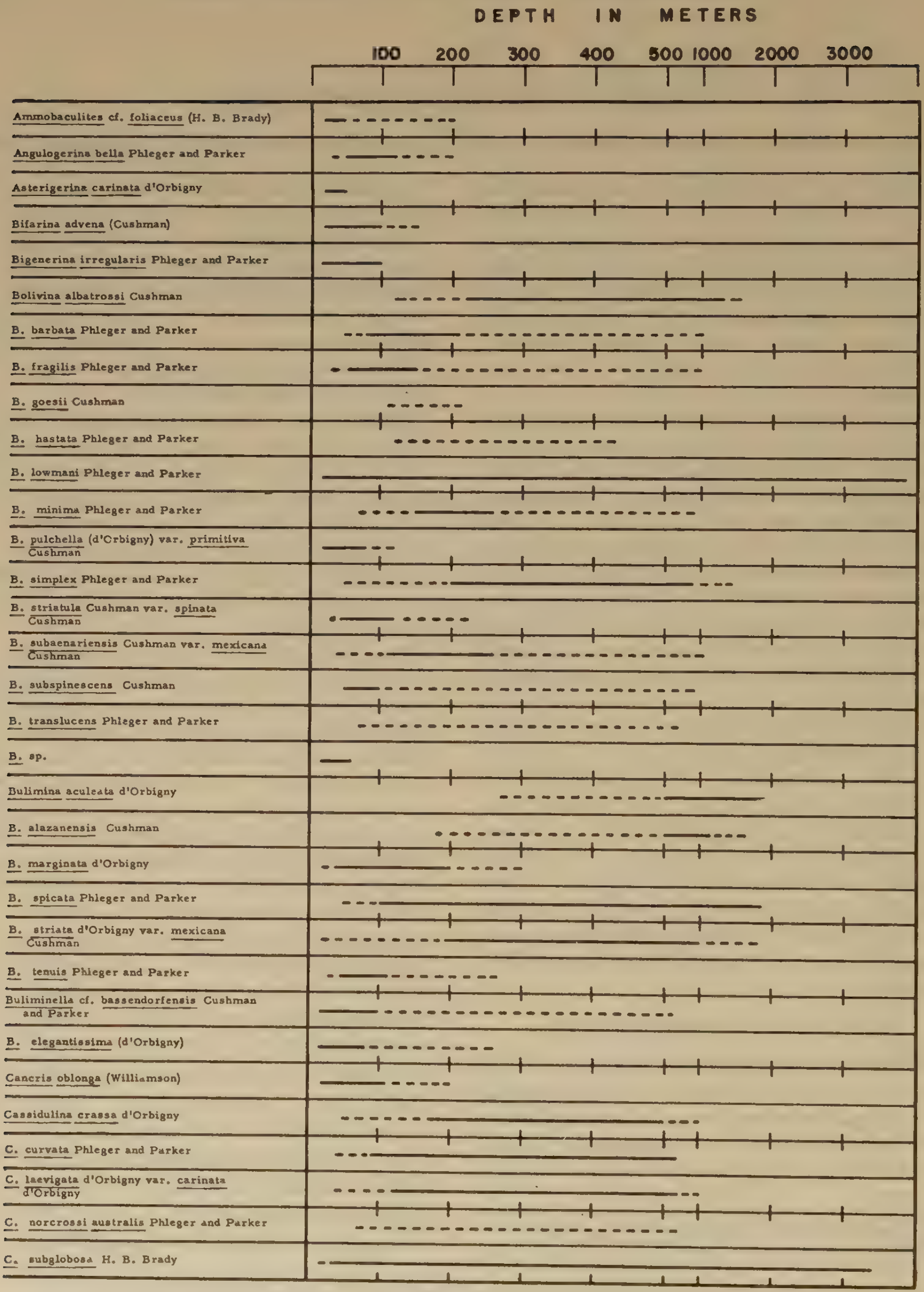

FIGURE 55.—Generalized depth ranges of benthonic Foraminifera in the Gulf of Mexico. Solid lines indicate relatively greater abundance than dashed lines.

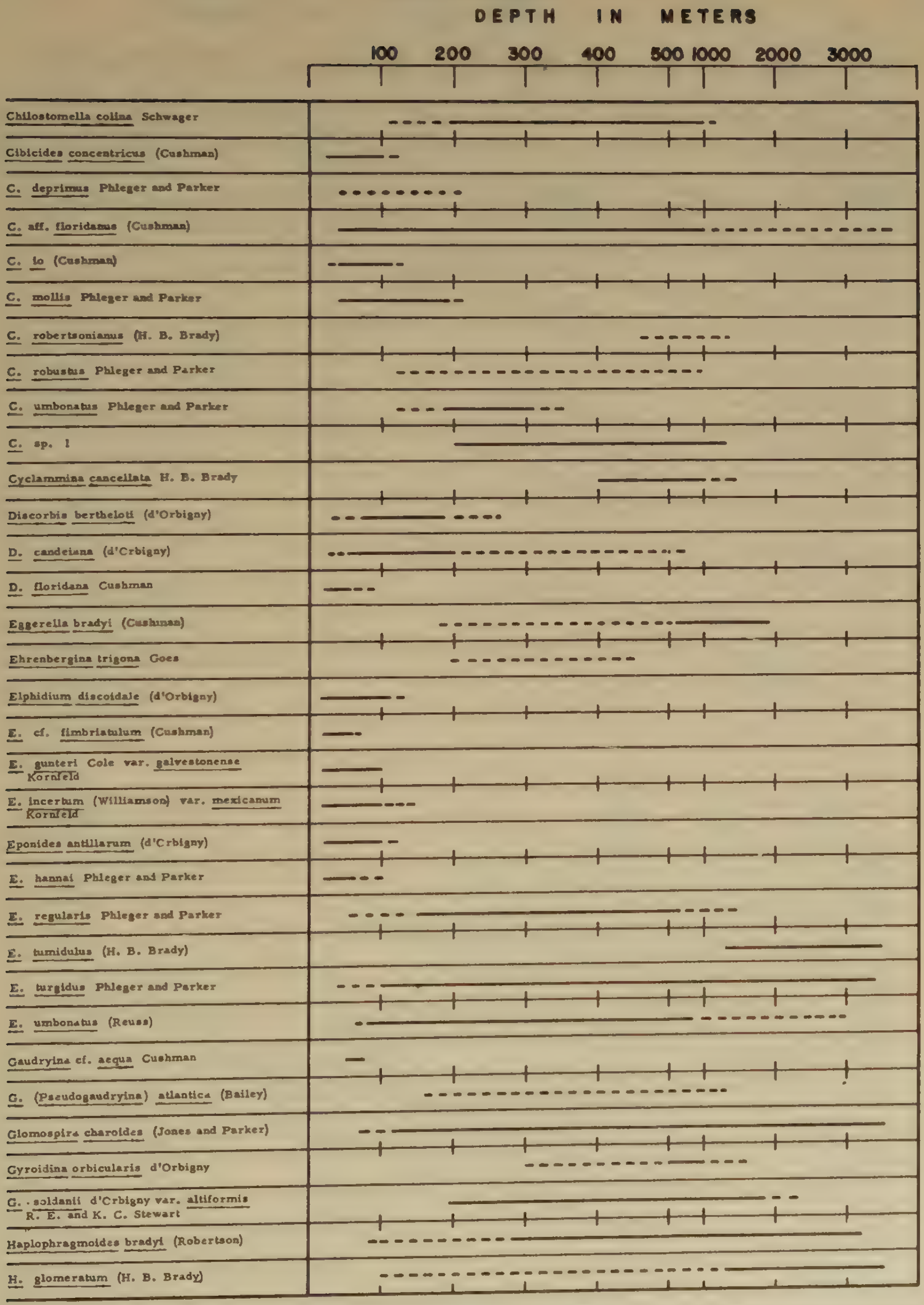

FIGURE 56.—Generalized depth ranges of benthonic Foraminifera in the Gulf of Mexico. Solid lines indicate relatively greater abundance than dashed lines.

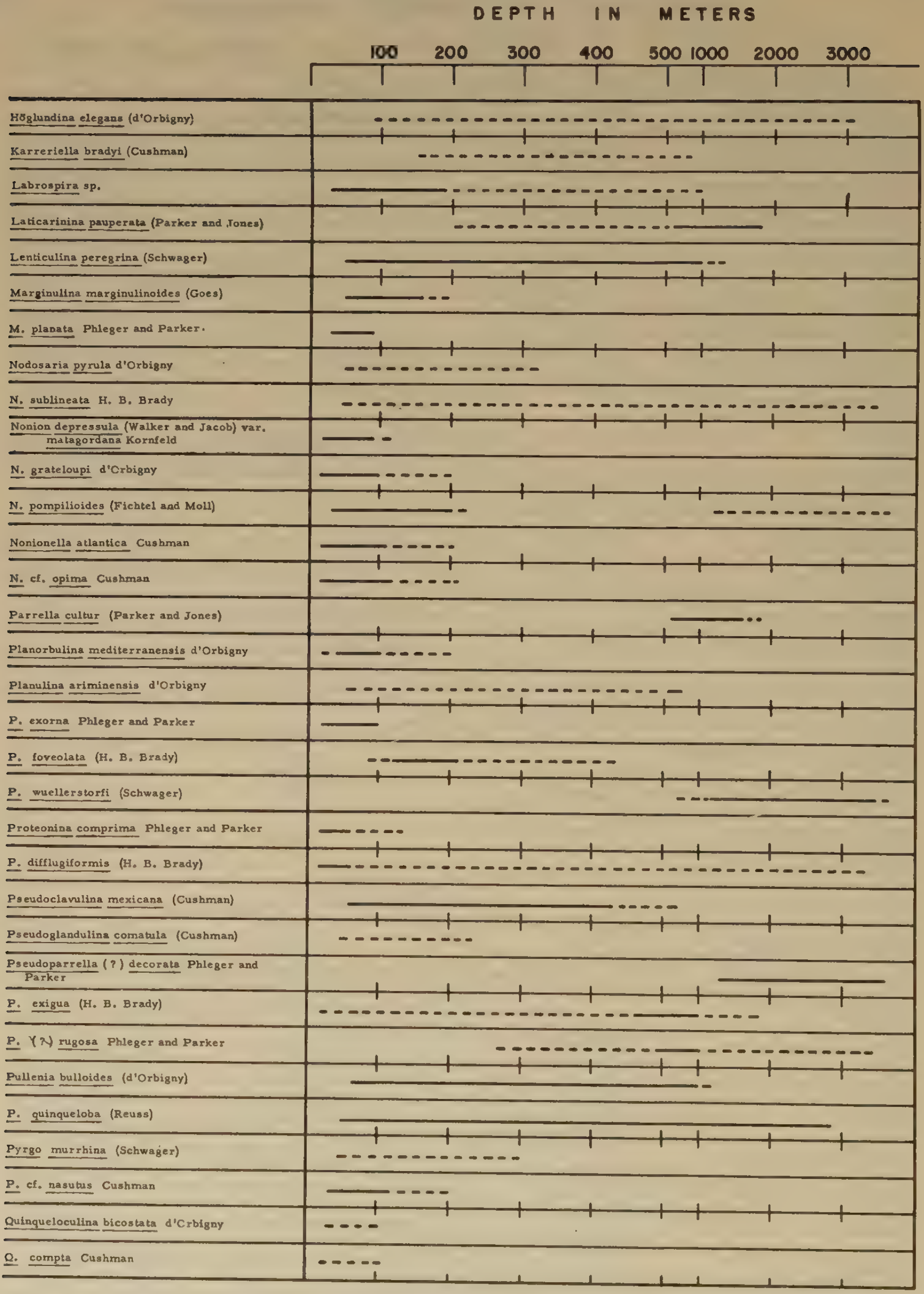

FIGURE 57.—Generalized depth ranges of benthonic Foraminifera in the Gulf of Mexico. Solid lines indicate relatively greater abundance than dashed lines.

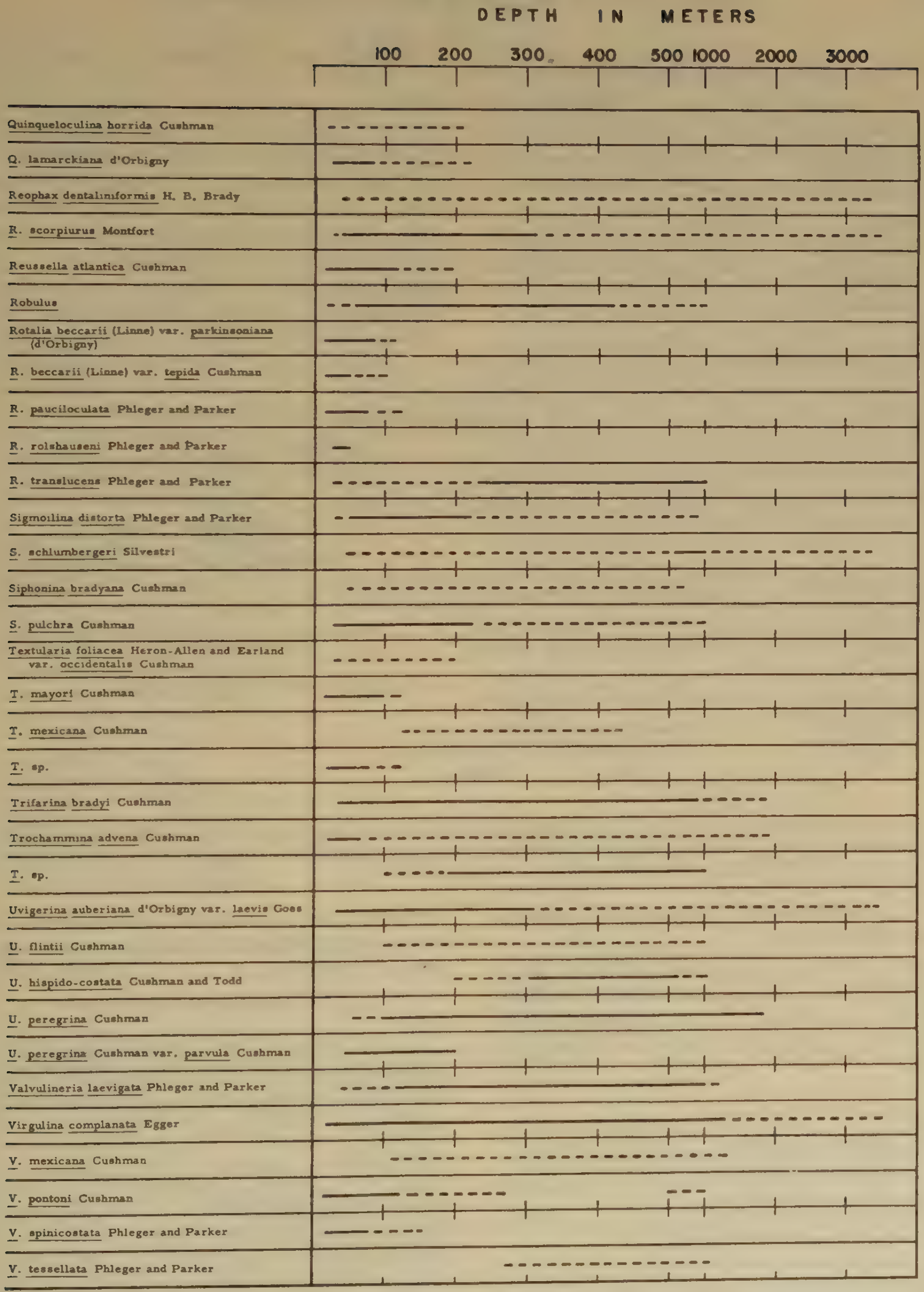

FIGURE 58.—Generalized depth ranges of benthonic Foraminifera in the Gulf of Mexico. Solid lines indicate relatively greater abundance than dashed lines.

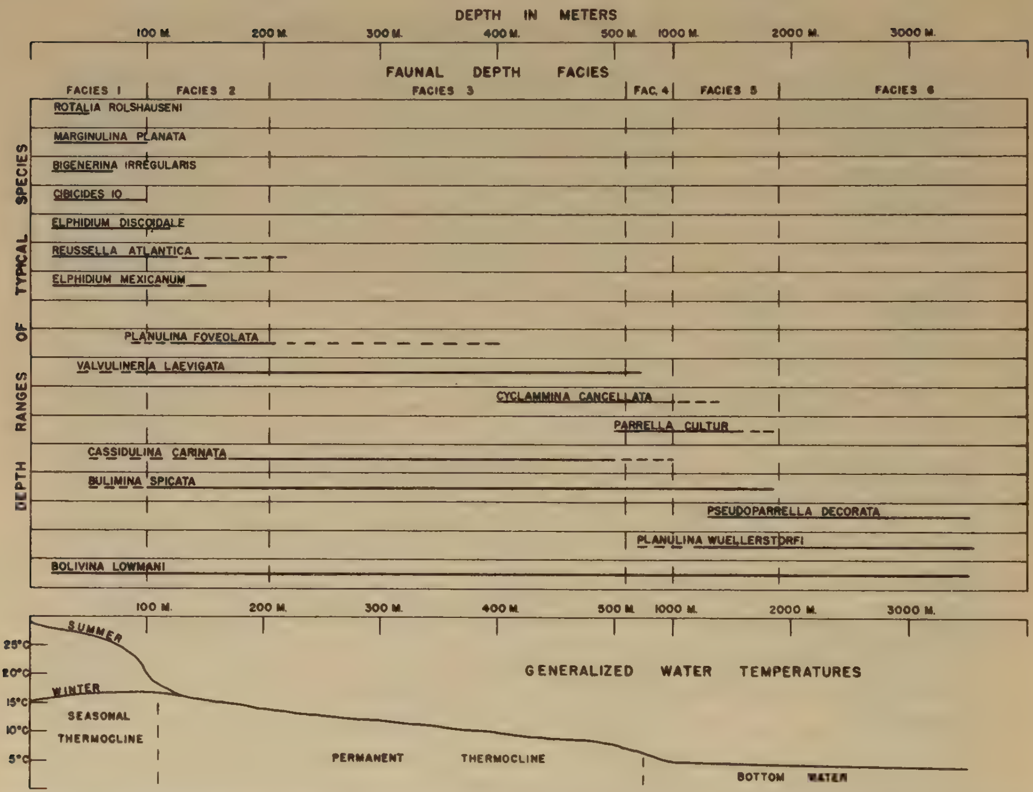

Figure 59.—Generalized chart showing depth biofacies of benthonic Foraminifera in the Gulf of Mexico and correlation between depth biofacies and temperature. Depth range lines are of benthonic Foraminifera used to illustrate types of depth distributions found.

below the bottom of the permanent thermocline at about 800–1,000 m.

Living specimens have been collected of 78 benthonic species. The greatest number of living specimens were found of the following species, all of which are characteristic of the facies above 100 m.:

Bifarina advena (Cushman).
Bolivina lowmani Phleger and Parker.
B. striatula Cushman var. *spinata* Cushman.
Buliminella cf. *bassendorfensis* Cushman and Parker.
Cancris oblonga (Williamson).
Cibicides concentricus (Cushman).
Elphidium discoidale (d'Orbigny).
Nonionella atlantica Cushman.
Proteonina comprima Phleger and Parker.
Rotalia beccarii (Linné).
Virgulina pontoni Cushman.

The highest production rate of benthonic Foraminifera is in the upper facies, although the largest population of accumulated empty tests in bottom sediments usually is at intermediate depths.

Calcareous areas.—The Foraminifera fauna of the calcareous areas is quite distinctive from that of the clastic areas and is dominated by *Amphistegina lessonii* d'Orbigny, a typical calcareous species.

Cushman (1922) described the Foraminifera from several environments of the Dry Tortugas area off the southwest coast of Florida. The sampling was too scattered to give dependable results of the distribution in these environments, some being represented by only one or two stations. For this reason, the following description includes only the outstanding characteristics of the area.

The area sampled is in shallow water with a maximum depth of 33 m. but chiefly 20 m. or less. The bottom sediment at the majority of stations is described as "fine white sand" or "sand"; this is calcareous sand. The fauna closely resembles that of the general West Indies region which, in turn, is similar to the warm, shallow faunas of the Indo-Pacific. Cushman described about 150 species from the area. The following list includes many of the most widely distributed and common species described:

Amphistegina lessonii d'Orbigny.
Archaias angulatus (Fichtel and Moll).
A. compressus (d'Orbigny).
Asterigerina carinata d'Orbigny.
Bigenerina irregularis Cushman and Parker.
Bolivina pulchella (d'Orbigny).
Cymbalopora squammosa (d'Orbigny).
Discorbis candeiana (Cushman).
D. mira Cushman.
D. subaraucana Cushman.
Elphidium discoidale (d'Orbigny).
E. poeyanum (d'Orbigny).
Triloculinella circularis (Bornemann).
Nonion grateloupi (d'Orbigny).
Pyrgo subsphaerica (d'Orbigny).
Quinqueloculina agglutinans d'Orbigny.
Q. lamarckiana d'Orbigny.
Q. laevigata d'Orbigny.
Rotalia rosea (d'Orbigny).
Spiroloculina antillarum d'Orbigny.
Textularia agglutinans d'Orbigny.
T. candeiana d' Orbigny.
Triloculina rotunda d'Orbigny.
Virgulina punctata d'Orbigny.

The *Amphistegina* fauna also is reported from an isolated calcareous reef area in the northwest Gulf of Mexico.

PLANKTONIC FORAMINIFERA

Planktonic Foraminifera are abundant in offshore areas of the northwest Gulf of Mexico off the continental shelf both as accumulations of tests in the sediments and as living members of the planktonic population. Occasional concentrations of planktonic specimens are found in shallow water. The planktonic fauna is dominated by great abundance of *Globigerinoides rubra* (d'Orbigny) and contains the following additional species in the surface bottom sediments:

Candeina nitida d'Orbigny.
Globigerina bulloides d'Orbigny.
G. eggeri Rhumbler.
G. inflata d'Orbigny.
Globigerinella aequilateralis (H. B. Brady).
Globigerinoides conglobata (H. B. Brady).
G. sacculifera (H. B. Brady).
Globorotalia menardii (d'Orbigny).
G. punctulata (d'Orbigny).
G. scitula (H. B. Brady)
G. truncatulinoides (d'Orbigny).
G. tumida (H. B. Brady).
Orbulina universa d'Orbigny.
Pulleniatina obliquiloculata (Parker and Jones)
Sphaeroidina bulloides d'Orbigny.
Sphaeroidinella dehiscens (Parker and Jones).

Living specimens of all but 6 of these species have been found in serial plankton tows taken from various depths of water at 27 stations occupied during February and March 1947. The average living planktonic Foraminifera population from these samples is about 5–6 specimens a cu. m. of water at 25–50 m. water depth, and much larger shallow-water populations are found in certain localities. Living specimens were collected at all depths of water sampled down to about 1400 m., but the largest population is in the upper layers at most stations. At a few stations there was a larger population collected at considerable depth than from near the surface. Nine specimens of planktonic Foraminifera, comprising six species, were found living on the surface of the bottom sediments.

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MARINE BACTERIA AND FUNGI IN THE GULF OF MEXICO[1]

By Claude E. ZoBell, *Scripps Institution of Oceanography, University of California*

Although the marine environment around the West Indies was one of the first to be examined by a bacteriologist (Fischer 1886) and has since been quite extensively studied (Drew 1912; Bavendamm 1932), there are very few published reports on bacteria and fungi in the nearby Gulf of Mexico. The author has been actively interested in the Gulf coast area since 1940, but the semiconfidential nature of the research projects has contraindicated the publication of the results. This paper summarizes personal observations in the region along with published reports that have a direct bearing upon microbiological conditions in the Gulf of Mexico where observations have been confined almost exclusively to regions near shore. The rather extensive but scattered literature on marine microbiology has been reviewed by Issatchenko (1914), Bavendamm (1932), Benecke (1933), ZoBell and Upham (1944), and ZoBell (1946a, 1947). Also noteworthy is the comprehensive article by Williams (1951) on the occurrence, importance, and characteristics of bacteria in the sea.

Waters of the littoral zone in the Gulf of Mexico are veritable bacterial gardens. At scattered stations from Tortugas to Aransas Pass, where water samples have been examined, bacterial populations ranging from thousands to many million per ml. have been observed. Large numbers of living bacteria have also been found in bottom sediments. The methods employed by various investigators for collecting and analyzing samples of water and marine sediments for numbers and kinds of bacteria have been summarized by ZoBell (1946a).

The abundance of bacteria in shallow Gulf waters, which greatly exceeds the abundance of bacteria in the open ocean, is believed to be attributable primarily to the higher content in the former of organic matter and suspended solids, both of which promote the growth of bacteria. The influx of fresh water with its load of organic nutrients from land drainage is also a contributing factor along the littoral zone. Here there is a commingling of both fresh-water and marine microorganisms and numerous transitional stages of both kinds. The observations of Berkeley (1919), Korinek (1926), Lipman (1926), Burke and Baird (1931), ZoBell and Feltham (1933), Burke (1934), and others indicate that ordinarily bacteria from fresh-water or terrestrial sources do not survive very long in sea water, but if the transition to the salt-water environment is gradual, as in brackish water of increasing salinity, a good many fresh-water forms may become acclimated to the marine environment (ZoBell and Michener 1938).

The bacterial flora of the Gulf coast region is characterized by exceptional biochemical versatility, cultures having been isolated that catalyze the transformation of virtually all types of organic matter and a good many inorganic substances. In the latter category are autotrophic bacteria of various kinds that oxidize hydrogen sulfide either in darkness or under the influence of sunlight (van Niel 1931, 1944). Autotrophs which oxidize ammonia to nitrite appear to be more common in surface water and sediment than those which oxidize nitrite to nitrate (Carey 1938). Methane oxidizers (Hutton and ZoBell 1949) were found in the topmost portions of mud samples from the Gulf coast region, and sulfate-reducing bacteria which oxidize molecular hydrogen as the sole source of energy were found in numerous samples from considerable depth (Sisler and ZoBell 1950).

Besides modifying inorganic substances, autotrophic bacteria are primary producers of organic matter. While some obtain their energy from sunlight in the manner of other photosynthetic plants, most autotrophic bacteria obtain their energy for the reduction of carbon dioxide from the oxidation of substances such as hydrogen sulfide, hydrogen, methane, ammonia, or nitrite.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 661. This paper is a contribution from the American Petroleum Institute Research Project 43A.

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Quantitative data on the relative amounts of organic matter synthesized by autotrophic bacteria are not available, but judging from the abundance of such bacteria and the quantities of ammonia, hydrogen, methane, or other substance believed to be oxidized, organic production from this source may be appreciable.

The chief function, however, of bacteria in the marine environment is in the mineralization or modification of organic matter (Waksman 1934). Among the organic materials found to be attacked by marine micro-organisms are sugars, starches, celluloses (Bavendamm 1932; Waksman et al., 1933), pectins, glucosides, fatty acids (Thayer 1931), triglycerides, alcohols, sterols, proteins, amino acids, chitins (Hock 1940), lignins, agar (Stanier 1941; Humm 1946), and hydrocarbons (ZoBell 1950a). These organic substances are attacked by both aerobic and anaerobic bacteria.

From Gulf of Mexico mud, Campbell and Williams (1951) isolated 20 strains of aerobic chitin-decomposing bacteria, including species of *Achromobacter*, *Flavobacterium*, *Micrococcus*, and *Pseudomonas*. Several of the cultures were actively proteolytic and/or lipolytic.

Mixed cultures from marine mud tend to decompose the organic remains of plants and animals (Waksman 1934) in aerobic environments with the formation of carbon dioxide, ammonia, sulfate, phosphate, and other oxidation products at a rate which is primarily a function of the temperature. In the absence of free oxygen the rate at which organic matter is modified by bacteria may be much slower, and, while there may be much mineralization of organic substances, in anaerobic environments certain constituents may be reduced or hydrogenated to form the mother substance of petroleum (ZoBell 1950b).

The action of heterotrophic bacteria is not confined to the decomposition of particulate organic materials. Dissolved organic matter is also utilized, it having been shown by ZoBell and Grant (1943) that under static conditions bacteria may reduce the organic content of sea water to less than 0.1 mgm./L. According to Waksman and Carey (1935), roughly 60 percent of the organic carbon is oxidized by aerobes to carbon dioxide and the remaining 40 percent is assimilated for conversion into bacterial protoplasm. The latter, being particulate, becomes available as a source of food for protozoa, copepods, filter feeders, detritus feeders, and grazing animals in general.

Krizencky and Podhradsky (1927) regard the conversion of dissolved organic matter into particulate matter utilizable by animals as one of the most important functions of bacteria in aquatic environments. The importance of bacteria as food for animals has been emphasized by the work of Baier (1935), MacGinitie (1935), Voroschilova and Dianova (1937), Mare (1942), and ZoBell and Feltham (1938). The latter workers (1942) estimated that around 10 grams (dry weight) of bacterial organic matter is produced per day per cubic foot of mud in a shallow marine mud flat. In summarizing the ecological function of bacteria on sand beaches, Pearse et al. (1942) point out that besides serving as food for small animals, bacteria are important scavengers, and they produce plant nutrients, including ammonia, nitrite, nitrate, and phosphate. From thousands to millions of living bacteria were found in beach sands at Beaufort, North Carolina.

Large numbers of bacteria were found by Williams et al. (1952), to be associated with the bay shrimp, *Penaeus setiferus*, taken from Aransas Bay and from the Gulf in the region of Galveston. Species of *Achromobacter*, *Bacillus*, *Micrococcus*, *Pseudomonas*, *Alcaligenes*, and *Flavobacterium* predominated in the order named. Most of the attached bacteria were carried by the cephlothorax portion of the shrimp. The optimum temperature for the growth of the bacteria was around 25° C., but most of the 1,200 cultures examined grew slowly at 4° C. Neither coliforms nor enterococci were detected by Williams and Rees (1952) in the intestinal tract of shrimp, suggesting that such bacteria have sanitary significance.

Another important function of bacteria is as symbionts in the alimentary canal of most marine animals where they aid in the digestion of chitin, cellulose, pectin, lignin, and other organic complexes. Similarly, certain shipworms and wood borers are believed to depend upon commensal bacteria which help to digest cellulose and lignin.

On the other hand, a small percentage of the microbial flora is pathogenic for plants or animals. Fish, Crustacea, shellfish, and other marine animals in nearly all stages of development may be susceptible to microbial infections; the pertinent literature on this subject has been annotated by ZoBell (1946a). Seaweeds, diatoms, dinoflagellates, and other marine plants may be extensively parasitized by pathogenic bacteria, actinomyces, yeasts, and mold fungi. The wasting disease of eelgrass, which threatened the extermination of *Zostera marina* along the Atlantic seacoast a few years ago, is believed to be due to infection by *Labyrinthula* species (Renn 1936), although *Halophiobolus* species may also be involved (Barghoorn and Linder, 1944).

By vitiating the water in local environments or in the wake of periods of intense organic productivity, bacteria may have far-reaching adverse effects on the plant and animal populations. Among the ways in which bacteria contribute to the vitiation of aquatic environments are by depleting dissolved oxygen, by producing hydrogen sulfide, by forming toxic amines, or by changing the pH of the water. So-called stagnant water basins are rendered uninhabitable primarily by the activities of bacteria, and extensive areas in the open ocean may become temporarily lethal for plants or animals. For example, Copenhagen (1934) described an area approximately 25 by 200 miles in the Atlantic Ocean off Walvis Bay, South Africa, where hydrogen sulfide is liberated periodically by bacterial activity in quantities sufficient to kill both flora and fauna. The bacterial vitiation of water is believed by the writer to be an important feature of the "red tide." Extensive populations of purple sulfur bacteria, observed by Gietzen (1931) growing associated with decomposing algae along the Holstein coast, imparted a distinctly red coloration to the sea.

Marine bacteria also contribute to the biofouling of man-made structures. The attachment and growth of barnacles, bryozoans, tunicates, mussels, clams, algae, and other fouling organisms on ships' bottoms or other submerged surfaces may be promoted by bacteria in various ways (ZoBell and Allen 1935). Likewise, microorganisms may contribute either directly or indirectly to the deterioration of pilings, planks, and other wooden structures in sea water. Lines, ropes, nets, seines, sailcloth, and other cordage or textile products readily rot in sea water unless they are treated to preserve them from microbial decomposition (Atkins and Warren 1941). Unprotected steel and iron structures are also susceptible to attack by bacteria which oxidize ferrous iron, produce acids, form hydrogen sulfide, create reducing conditions, or depolarize hydrogen films resulting from the reaction between water and iron. Acid production in microspheres from the bacterial oxidation of organic matter or sulfur may result in the corrosion of concrete. Even rubber and bituminous coating materials may be attacked by marine micro-organisms (ZoBell 1950a).

Bacteria are important chemical and geological agents in marine bottom deposits where they promote many processes involving organic compounds, inorganic constituents, and physicochemical conditions that affect the modification or diagenesis of sediments. One of the first geochemical processes to be studied by microbiologists was calcium carbonate precipitation which Drew (1911a, b) attributed to the activities of denitrifying bacteria found in great abundance in shallow subtropical seas in the vicinity of Jamaica and Tortugas. He (1912) reported that marine mud near the Bahamas contained an average of 160 million bacteria per ml. with *Bacillus calcis* predominating. Working in the same region, Kellerman and Smith (1914) confirmed Drew's hypothesis on the precipitation of calcium carbonate by bacteria which raise the pH by reducing nitrate, by producing ammonia, or by utilizing organic acids.

After finding rather sparse bacterial populations in the open sea around Tortugas, Lipman (1929) questioned whether bacteria contribute significantly to calcium carbonate precipitation. This view was rendered untenable, however, by the extensive observations in the Bahamas of Bavendamm (1932) who concluded that calcium carbonate precipitation in tropical seas is primarily a microbiological process. Similar conclusions were reached by Gee (1932) who investigated bacterial activity in the Florida Keys. Micro-organisms found there by Gee and Feltham (1932) promoted the precipitation of calcium carbonate by producing ammonia and otherwise increasing the pH.

The pH of marine sediments may be increased by micro-organisms which (1) form ammonia, (2) reduce nitrate or nitrite, (3) reduce sulfate, (4) oxidize or decarboxylate organic acids, or (5) utilize CO_2. On the other hand, the (1) production of CO_2 or organic acids, (2) oxidation of hydrogen sulfide or sulfur, (3) formation of nitrate, (4) assimilation of ammonia, or (5) the liberation of phosphate from organic compounds are microbial processes that tend to decrease the pH of their environment. Reactions ranging from pH 6.8 to 8.7 in Gulf coast sediments are believed to be attributable, at least in part, to microbial activities. Similarly, bacteria and allied micro-organisms are believed to be the principal dynamic agencies that create conditions in marine sediments sometimes as reducing as $E_h -460$ millivolts (ZoBell 1946b).

The general tendency is for micro-organisms to mineralize the organic remains of plants and animals in marine sediments. In highly reducing environments, however, the microbial decomposition of organic matter may result in residues relatively richer in hydrogen and correspondingly poorer in oxygen, nitrogen, sulfur, and phosphorus. This results in the accumulation of organic complexes that are more petroleum-like than their predecessors (ZoBell 1950b). The microbial formation of methane is a common property of recent marine sediments, and there is pretty good evidence that bacteria also produce higher hydrocarbons. While there is no reason to believe that bacteria produce petroleum, they may contribute in many ways to its formation. The high organic productivity and rapid rate of sedimentation in Gulf coast waters suggest this region as a potential source bed of petroleum.

Petroleum hydrocarbons may be modified in recent sediments by micro-organisms. Both aerobic and anaerobic bacteria which attack petroleum hydrocarbons were detected in nearly all 1-gram samples of surface mud collected from shallow water along the coasts of Louisiana and Texas. From hundreds to millions of such micro-organisms per gram of mud were demonstrated by the minimum dilution method.

Sulfate-reducing bacteria were also found in abundance, some at core depths exceeding a hundred feet. Sulfate reducers form hydrogen sulfide, and they may account for the formation of sulfur. The recovery of sulfate reducers having unique tolerance for temperature, salinity, and hydrostatic pressure from oil and sulfur wells suggests that they may be indigenous species in ancient marine sediments (ZoBell and Rittenberg 1948). A large percentage of the sulfate reducers isolated from Gulf coast sediments can utilize molecular hydrogen (Sisler and ZoBell 1950).

Several other physiological types of bacteria, that may function as geochemical agents, have been found in marine sediments, but their importance can be assessed only after they have been more thoroughly studied.

Marine fungi, including yeasts and molds, are found almost exclusively in water and the topmost layers of sediment. Being heterotrophs, such fungi are closely associated with organic substances. Both yeasts and molds commonly occur growing either saprophytically or parasitically on marine plants and animals. According to Sparrow (1936), who isolated 18 new species of mold fungi from the Woods Hole region, marine fungi have been even less completely studied than marine bacteria. Barghoorn and Linder (1944) were impressed by the diversity of fungi found in the sea. A good many of the fungi species isolated from the sea are quite unlike any known terrestrial species. They grew better in sea water than in corresponding fresh water media, and some species developed in media containing three times as much salt as normal sea water.

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662

MICROFILTRATION IN OCEANOGRAPHIC RESEARCH

II. RETENTION OF COLLOIDAL MICELLES BY ADSORPTIVE FILTERS AND BY FILTER-FEEDING INVERTEBRATES; PROPORTIONS OF DISPERSED ORGANIC TO DISPERSED INORGANIC MATTER AND TO ORGANIC SOLUTES[1]

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ABSTRACT

To adsorb and retain quantitatively the minute colloidal micelles held in dilute suspensions, fine inert inorganic powders (such as MgO and refined diatomaceous earth) or finely porous cellulose membranes may be employed. Minute micelles, such as molecular hemoglobin, are retained also by setous or ciliary-mucous filter-feeders. Microfiltration is applicable in preparing bacteria-free aqueous filtrates and in determining the preponderance of organic *dispersoids* over organic *solutes* in natural waters. Molecular filter membranes have been used to demonstrate the high variability of total leptopel concentrations and to indicate the inconstancy of ratios between organic and inorganic dispersoids.

Current studies of marine biochemical cycles involve the use of adsorptive filters for the recovery, concentration and quantitative studies of leptopel, the finely particulate organic and inorganic matter suspended in water (Fox, Isaacs and Corcoran, 1952; Goldberg, Baker and Fox, 1952). Although careful experimentation indicated that marine hydrocolloidal micelles must be quantitatively retained either by adsorptive powder filters or by cellulose acetate and nitrate molecular filter (MF) membranes, it was necessary to resolve other critical questions, such as (a) the fineness of micelles retainable by such filters, (b) ratios between quantities of organic and inorganic leptopelic components, and (c) proportions between finely *particulate* and truly *dissolved* organic matter in the sea. These problems have involved (1) testing each type of filter for its retention of extremely small micelles of approximately known size, such as hemoglobins, (2)

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determining the total dry weight and ash weight of leptopel retained by ashless MF membranes, and (3) measuring the biochemical oxygen demand of endemic marine micro-organisms which utilize total organic matter in raw samples of sea water, comparing such measurements with determinations of the micro-organisms' use of dissolved molecules which remain in filtered samples. The removal of bacteria from sea water systems with each type of filter has also been confirmed (cf. Goetz and Tsuneishi, 1951; Clark and Kabler, 1952).

RETENTION OF COLLOIDAL MICELLES BY ADSORPTIVE FILTERS

Substances Tested and Their Properties

(a) Oxyhemoglobin from a tide-pool blenny (not specifically identified) and from the marine goby *Gillichthys mirabilis;* micellar size of vertebrate hemoglobins = ca 50 Å (McBain, 1950: 128); molecular weight, ca 70,000.

(b) Oxyhemoglobin from the marine polychaete worm *Thoracophelia mucronata;* micellar size two- to ten-fold that of the fish hemoglobin as estimated by ultramicroscopic (dark-field cardioid condenser) examination of both species. Suspensions of about 2 ppm were used in experiments.

Filters and Reagents

(a) Adsorptive powder filters: equal parts of finely powdered MgO (reagent grade) and pure SiO_2 as "Super-cel," a refined diatomaceous earth (Fox, Isaacs and Corcoran, 1952).

(b) Molecular filter (MF) membranes of finely porous cellulose acetate-nitrate (Goldberg, Baker and Fox, 1952).

(c) Freshly prepared (or carefully preserved and always pretested) solutions of benzidine in equivalent parts of glacial acetic acid and hydrogen peroxide (Hawk, Oser and Summerson, 1947).

(d) Special adsorptive refiltering medium consisting of 5 parts Super-cel and 1 part $Ca(OH)_2$ to retain hemoglobin quantitatively from suspensions of 1 part or less in 10^8. This medium, less active than MgO in gradually catalyzing the decomposition of H_2O_2 to yield a "blank" blue color reaction with benzidine, is used for reprocessing filtrates from the other microfiltrational devices. Traces of hemoglobin, retained in suspensions too dilute to yield a positive benzidine reaction on a direct test of the filtrate, are readily detected by passing the fluid through the thin powder pad and by finally applying the test directly to the pad's damp upper surface where any traces of residual hemoglobin would have been concentrated. Powders containing $Ca(OH)_2$ are more effective with sea water than with distilled or fresh water, since, in the former medium, the sparingly soluble base immediately precipitates gelatinous flocks of insoluble and strongly adsorbent $Mg(OH)_2$.

Precautions

(a) Adsorptive powder-filter suspensions should be allowed to settle for a few minutes in the porous cup, should be firmly packed into position by initial suction before using, and should remain covered with water at all times in order to preclude the formation of cracks or other channels.

(b) Use of excessive amounts of $Ca(OH)_2$ should be avoided in the filtration of sea water systems, since any considerable proportions of the resulting $Mg(OH)_2$ precipitate tend to clog the filter.

(c) An excess of the neutral adsorbent must be present, since this filtrational process is one of *adsorption* rather than mere physical screening. Hence a given quantity or surface area of the adsorbent will possess a limiting saturation value which, if exceeded by the concentration of the adsorbate (e. g. hemoglobin), will allow micelles of the latter to pass.

(d) Numerous types of surface, including the finely powdered MgO-Super-cel mixture, catalyze the decomposition of H_2O_2, thus yielding free O_2 which reacts with benzidine. However, the blue color thus produced appears rather slowly in contrast with the instantaneous manifestation of green or blue-green colors produced by adsorbed hemoglobin. Moreover, this "blank" blue reaction is still more retarded when $Ca(OH)_2$ has been substituted for MgO as a sea water filter. If these factors are kept in mind, there is no difficulty in recognizing the presence of adsorbed hemoglobin.

Results. Four-liter suspensions of fish hemoglobin that had been separated from the laked corpuscular envelopes, and of worm hemoglobin, were resolved by filtration through adsorptive powder columns [0.5 g MgO; 0.5 g Super-cel, and optionally 0.1 g $Ca(OH)_2$] of about 4 mm thickness. Hemoglobin concentrations of 2 ppm or 8 mg total were used in both sea water and distilled water. Following the operation, the damp filter-cake was removed and the benzidine test was applied. Its top surface responded positively at once while the bottom surface was negative; cross sections of the fractured cake showed that the hemoglobin was adsorbed in the upper 1 to 2 mm; its quantitative adsorption was clearly indicated by a distinct color boundary part way through the cake. Complete removal of the hemoglobin was further confirmed by passing the filtrate from the first operation through a second adsorptive powder-cake of 5 parts

Super-cel and 1 part $Ca(OH)_2$; application of the benzidine test to its damp top surface gave negative results. Molecular filter membranes of different porosities were likewise employed for processing similar volumes of dilute, laked and cleared hemoglobin suspensions in sea water and in distilled water. The resulting filtrates were then tested for residual hemoglobin by using the Super-cel-$Ca(OH)_2$ powder as above.

The following filter membranes which were used are designated by their Z-number (time in seconds required for 1 ml of water to pass through 1 cm^2 of surface area at 700 mm pressure) and their VC value (volume ratio of cellulose material to air space).

Filter No.	*Z No.*	*V C*	*Hemoglobin in distilled water*	*Hemoglobin in sea water*
5001–12	0.035	....	Passed	Passed
1152–6	0.26	0.142	Passed	Passed
2010	1.0	0.200	Sometimes passed little*	Sometimes passed traces*
1122–5	2.6	0.213	Sometimes passed little*	Sometimes passed traces*
1122–3	8.0	0.249	——	Retained all
1152–8	20.0	0.269	Retained all	Retained all

* We believe that in some instances adventitious soluble heme degradation products might have passed through the filter, since heme crystals dissolved in water give a strong reaction with benzidine. Furthermore, while the test failed at a dilution of 1 : 25,000, it responded after the heme from this solution had been retained on a Super-cel + $Ca(OH)_2$ filter

From the foregoing experiments it is concluded that the MgO + Super-cel adsorptive powder, as well as cellulose filters of fine porosities, will quantitatively adsorb extremely fine micelles (such as vertebrate hemoglobin) from very attenuated suspensions, and that such microfiltrational operations are therefore suitable for the quantitative resolution of marine colloids. Indeed, most marine colloidal micelles are probably of much larger mean diameter than hemoglobin, and, in view of the presence of the divalent cations and charged micelles, they must occur in various degrees of adsorption, agglomeration or coacervation.

RETENTION OF DISPERSED HEMOGLOBIN BY FILTER-FEEDING INVERTEBRATES

Because our chief interest was concerned with the fineness of colloidal micelles which may be removed by filter-feeders, we conducted a few experiments on the retention of molecularly dispersed fish hemoglobin by two different and widely distributed marine invertebrates: a mysid crustacean (not specifically identified) which was collected in the vicinity of kelp beds and slicks off La Jolla; the sea mussel, *Mytilus californianus*, which grows in large numbers and is attached to intertidally exposed rocks and pier pilings.

Both control and experimental mysids were placed in previously microfiltered sea water. A small volume of laked and paper-filtered hemoglobin was then added to the microfiltered water that contained the experimentals, which, in contrast with the controls, conspicuously manifested the full dark-colored contents of their alimentary tracts. In numerous instances they had next day voided long dark rod-like fecal strands, which, upon microscopic inspection, especially after mashing under a cover glass, showed green or blue responses to the benzidine test, thus indicating the presence of heme or hemoglobin.

Similarly, both the pseudofeces and stomach rinsings of mussels exposed to dilute molecularly dispersed hemoglobin yielded green colors with benzidine while those of the control animals were negative in this regard. Likewise, the white experimentally talc-laden feces of mussels which had previously received hemoglobin exhibited purple colors with benzidine as well as positive tests for iron in the presence of thiocyanate.

These experiments are regarded as demonstrative of the ability of two representative filter-feeders (one setous, the other ciliary and mucous) to adsorb from suspension colloidal particles of such extremely fine dimensions as those of vertebrate oxyhemoglobin, i. e., 40 to 50 Å. Microfiltrational operations with adsorptive powders or molecular filters may be used to recover the dispersed phases of natural hydrosols, including colloidally dispersed materials commonly gathered by mucous or other filter-feeding aquatic animals.

PROPORTION BETWEEN ORGANIC AND INORGANIC LEPTOPELIC CONSTITUENTS

Goldberg, Baker and Fox (1952) have demonstrated in duplicate samples and with respect to depth the wide variability of finely particulate inorganic matter in the sea, while Fox, Isaacs and Corcoran (1952) have supplied similar information pertaining to organic leptopel. The inhomogeneity of these materials, their changing concentrations with time, and the variability in ratio between organic and inorganic leptopel, were confirmed with the molecular filter in two additional experiments reported here.

Two 4-liter samples, collected in relatively nonwettable polyethylene bottles, were taken from about 20 feet beneath the surface at the end of the Scripps Institution's pier, 1,000 feet offshore. Sample I was collected during a period of high surf, when the offshore waters contained much visible suspended matter; sample II was taken on the following day when the sea had subsided to a normal surf and when the water was less turbid. In the laboratory, the coarser particles of sand and mica settled out of suspension, and floating algal fragments were removed from the water surface.

Each 4-liter sample was passed through an ashless cellulose membrane filter ($Z = 2.6$). The residue was leached *in situ* with distilled water, and the membrane, with its retained particulate material, was then dried at 80° C for six hours in a vacuum oven. After weighing, each membrane was ignited, and the ash weight was recorded as follows:

	Total dry solids (mg/L)	*Ash (mg/L)*	*Organic matter by difference (mg/L)*	*Organic Matter (%)*
Sample I	10.5	4.0	6.5	62
Sample II	3.8	2.7	1.1	29

These two random samples thus exhibit nearly a three-fold variation in total leptopel content and more than a two-fold difference in the proportion of the organic component.

The value of 29% organic matter obtained from Sample II is close to the figure obtained previously for solid material collected from a marine slick (27%; Fox, Isaacs and Corcoran, 1952) and to the figure derived from several analyses of the flocculent portions of feces from a typical detritus filterer, the California mussel (31%; Fox and Coe, 1943).

PROPORTIONS BETWEEN DISPERSED AND DISSOLVED ORGANIC MATTER IN SEA WATER

Method. Samples of raw sea water were freshly collected in clean and relatively nonwettable plastic bottles. The untreated sea water and filtrates derived from it were assayed for their respective content of (a) original dispersed and dissolved organic matter combined, and (b) organic solutes by determining (with the Winkler method) the biochemical oxygen demand (B. O. D.) of multiple aliquots. The raw sea water already contained a normal flora of micro-organisms and was therefore ready for incubation. However, each of the filtered samples was inoculated with 5 ml raw sea water per liter in order to provide mixed populations of marine bacteria. This inoculation supplemented the organic matter by no more than 0.5% of the original supply. The multiple aliquots, incubated at 27 to 28° C in 60-ml glass-stoppered bottles, were analyzed for residual dissolved oxygen before incubation and at specified intervals (Figs. 1, 2, 3).

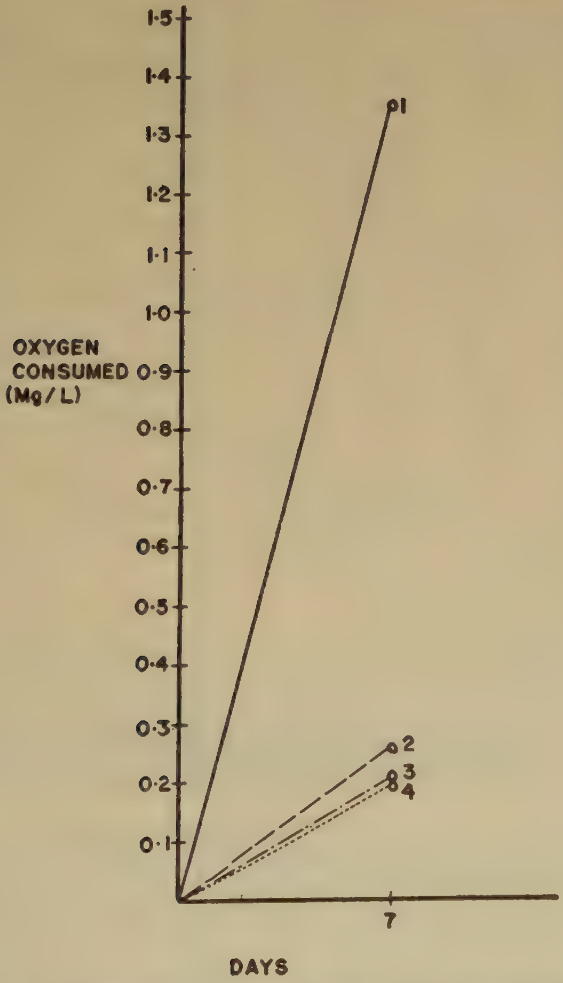

Figure 1. B. O. D. of sea water: (1) raw and untreated; (2) after powder treatment and paper filtration; (3) after powder filtration; (4) after MF filtration. Incubation temperature, 28° C; ratio between retained and filter-passing organic matter (7 days' incubation): ca 85 : 15%.

Results. Experiment I. Paired samples of sea water were incubated in the following stages: (1) in the raw state, (2) after occasional shaking with a little powdered MgO during a two-hour period and subsequent filtering by gravity through a superimposed pair of No. 50 Whatman filter paper cones, (3) following filtration by suction through a packed column of adsorptive powder (equal weights of MgO and

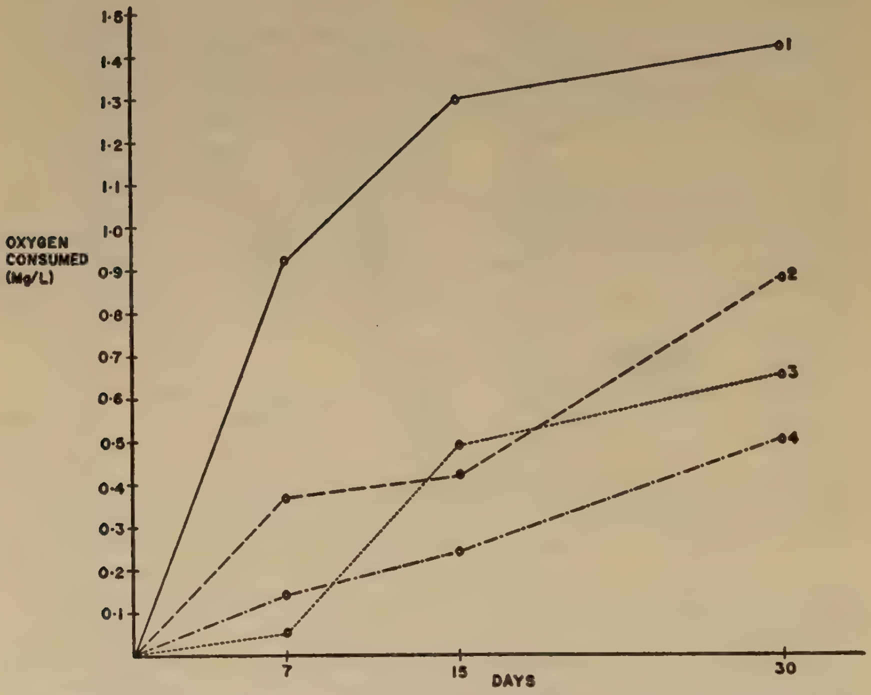

Figure 2. B. O. D. of sea water: (1) raw and untreated; (2) after powder treatment and paper filtration; (3) after powder filtration; (4) after MF filtration. Incubation temperature, 27° C; ratio between retained and filter-passing organic matter (i. e. comparing B. O. D. of curve 1 with the average values of curves 3 and 4 after 30 days): ca 60 : 40%.

Super-cel), and (4) after passage through a fine MF membrane ($Z = 8.5$). B. O. D. measurements were made after culturing for seven days at 28° C; the results are plotted in Fig. 1.

Experiment II. The above experiment was repeated with fresh sea water and with measurements of the B. O. D. of quadruplicate or triplicate aliquot samples after incubation for 7, 15 and 30 days at 27° C. Values for the average quantities of oxygen consumed are plotted in Fig. 2.

Experiment III. Since the rubber connections used in the assembly which employed adsorptive powder might have contributed traces of contaminating organic material to the filtrates, comparisons were made between the B. O. D. of sea water (1) before it was treated and (2) after it was filtered through the adsorptive powder in a Morton filter apparatus, which is constructed entirely of glass, i. e., with ground joint and a fine sintered glass disc that is capable of retaining

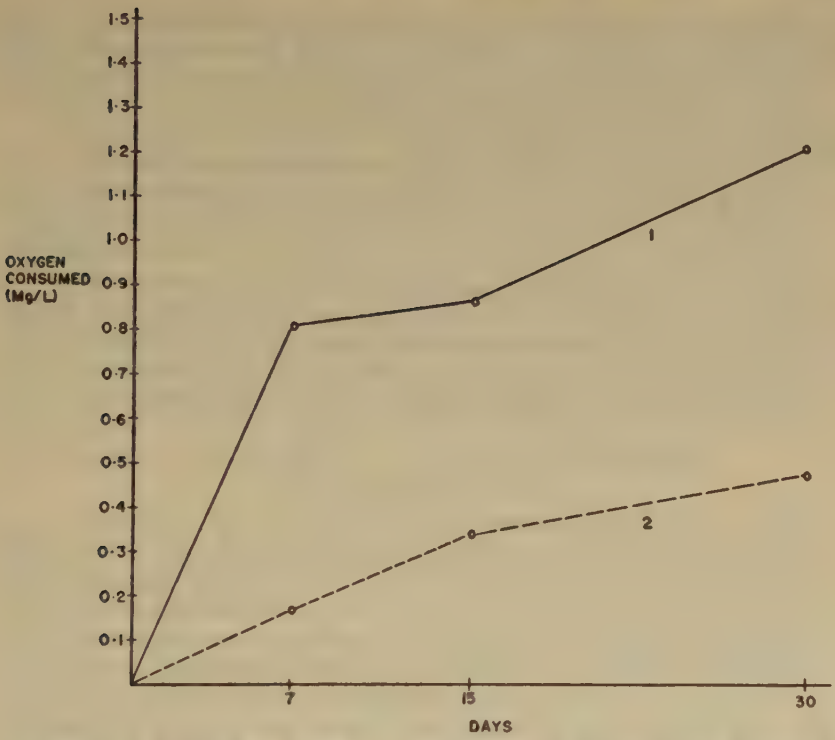

Figure 3. B. O. D. of sea water: (1) raw and untreated; (2) after powder filtration in all-glass Morton apparatus. Incubation temperature, 27° C; ratio between retained and filter-passing organic matter (30 days' incubation): ca 61 : 39%.

bacteria in filtrational sterilization of media. Before use, the whole apparatus was dismantled, its parts were treated separately with hot concentrated nitric or hot concentrated chromic and sulphuric acids, and all parts were ultimately rinsed free of acid with twice-distilled water. Average values of B. O. D. measurements, made on multiple aliquot samples of each medium after incubation for 7, 15 and 30 days at 27° C, are plotted in Fig. 3. Close agreement between the data in experiments II and III suggests that the former involved no contaminants.

From a study of the graphs it is apparent that the major proportion (3/5 or more) of the organic matter in sea water existed in a colloidal or other particulate state rather than in the dissolved condition. While traces of some organic solutes may be adsorbed by the powder or by the cellulose material of the molecular filter, it is highly improbable that such adsorption occurs to a significant extent, especially from such greatly diluted systems as are represented by normal sea water. The organic material in the filtrate, therefore, probably represents all of the true organic solutes. On the other hand, it seems certain that the adsorbent filters must have retained all of the colloidally dispersed and other finely particulate material.

B. O. D. measurements serve only as conservative indicators of the amount of organic matter present, since this may include refractory materials, e. g., chitin, lignin, humus and the like, which fail to yield quantitatively to the action of marine microflora even after 30 days at 27–28° C. Also, organic residues of at least 2 parts in 10^7 would probably apply to all cultures, since, according to ZoBell and Grant, marine bacteria fail to destroy organic matter at such dilute concentrations even after several months (ZoBell, 1946). Organic solutes in the sea exceed this value by about two-fold in the plotted data.

ADSORPTIVE REMOVAL OF BACTERIA BY MICROFILTRATION

Method. Both the adsorptive powder and the MF membranes were tested for their ability to retain marine bacteria quantitatively. The two types of apparatus were assembled in the regular way and were sterilized in an autoclave. The cellulose MF membrane itself ($Z = 1.4$), being heat-labile, was sterilized by exposure for four hours to an atmosphere of ethylene oxide and was installed aseptically for filtration just prior to use. In the other assembly, the heat-sterilized powder was added to the special sterile cup; sterile water, passed through to seat the powder pad, was received in a sterile test tube which was ultimately removed before the main operation.

Raw sea water, containing approximately 1,000 bacteria per ml, was processed through each filter. Filtrate samples 1 ml in volume were transferred to a series of tubes, each of which contained 5 ml of sterile nutrient sea-water broth (ZoBell, 1946: 41); incubation was then carried out at 27° C.

Results. After 72 hours of incubation, all tubes remained sterile. They were therefore inoculated with mixed marine bacteria to determine whether the filtrate had perchance contained any antibacterial contaminants. After reincubation at 27° C for 24 hours, the contents of all tubes were distinctly turbid, indicating bacterial growth.

It was concluded, therefore, that each type of filter is capable of removing all bacteria from sea water without destroying its ability to support bacterial multiplication. Bacterially sterile and leptopel-free sea water, ionically balanced and of low residual organic (solute) content, may be readily prepared for media or other purposes by aseptic microfiltration followed by equilibration with a stream of sterile filtered air.

SUMMARY

1. Microfiltration with fine, inert inorganic powders (e. g., MgO + Super-cel) or fine cellulose membranes will retain very fine colloidal micelles, such as molecular hemoglobin, which is adsorbable also by setous and by ciliary mucous-feeding animals (e. g., mysids and mussels).

2. The same types of adsorptive filters are also applicable in preparing bacteria-free aqueous filtrates and in determining the preponderance of *dispersed* over *dissolved* organic matter in natural waters.

3. Molecular filter membranes have been used to demonstrate the high variability of total leptopel concentrations and to indicate the inconstancy of ratios between organic and inorganic leptopelic components.

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WILLIAM G. VAN DORN

WIND STRESS ON AN ARTIFICIAL POND

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WIND STRESS ON AN ARTIFICIAL POND[1]

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ABSTRACT

The wind-induced slope of the surface in an 800-foot model-yacht pond has been measured to a relative accuracy of 5×10^{-7}. This slope is proportional to the sum of the surface and bottom stresses. The bottom stress was independently measured to an accuracy of 0.1 dynes cm^{-2} and was found to be negligible when compared to the surface stress. The surface slope is shown empirically to be the result of two effects: first, a tangential "friction" drag, which is invariably present and which is proportional to the square of the windspeed; and second, a "form" drag, which occurs only after the wind has increased above a certain value. The second affect is related to surface waves. Application of a detergent to the water eliminates both waves and form drag. The surface current was proportional to the windspeed and independent of waves. The slope increased with heavy rain, and a theoretical model is proposed which adequately predicts the observed increase.

The present study was modeled closely after Keulegan's experiments in a 60-foot laboratory channel. The results of the two studies agree quantitatively.

INTRODUCTION

Previous attempts to determine the stress exerted by the wind on a free water surface can be roughly divided into two groups. The first consists of measuring the vertical gradient of the mean horizontal wind velocity over a convenient range of elevations, converting this gradient into a shear stress (usually by Prandtl's mixing-length theory), and extrapolating this stress to the water surface by analogy to the empirical laws describing flow over a rigid boundary or by assuming the stress to be constant over a limited range of height above the surface. The second method involves measurements of the surface slope of a confined body of water under wind action, making use of the fact that under certain assumptions the slope is nearly proportional to the surface stress. This stress is then correlated with the wind at a stated height above the surface.

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Attempts to measure stress by the second method fall into two categories: those dealing with large natural bodies of water (Corkan, 1950; Ekman, 1905; Hela, 1948; Hellstrom, 1941; Palmén and Laurila, 1938; and others) and those in laboratory channels (Francis, 1951; Hellstrom, 1941; Keulegan, 1951). This paper deals with still another series of slope measurements made on an artificial pond 220 m long. Thus the scale was roughly intermediate between the two mentioned categories.

THEORY OF SURFACE SLOPE

The theoretical treatment of the shape of the free surface of a confined body of water acted upon by a uniform and steady wind has been given by Hellstrom (1941). The special case of a long, shallow, rectangular channel was investigated by Keulegan (1951) and Haurwitz (1951), but the role of the inertial terms was not discussed explicitly. We shall give a brief account below.

If we take the x-axis along the bottom in the direction of the wind, with the z-axis upwards (Fig. 1), neglect the Coriolis force and the horizontal pressure gradient, and assume that the water is homogeneous, then the equation of horizontal motion can be integrated to the following form,

$$\frac{\partial}{\partial t}\int_0^{H+h} u dz + \frac{\partial}{\partial x}\int_0^{H+h} u^2 dz = -\, g(H+h)\frac{\partial h}{\partial x} + \frac{\tau_s + \tau_b}{\rho}, \tag{1}$$

where u is the horizontal water velocity, H the undisturbed water depth, h the surface departure from the undisturbed state, ρ the water density, τ_s and τ_b the horizontal stresses at the surface and bottom respectively, and g the acceleration of gravity. This equation expresses the momentum budget of a column of water of unit area extending from the surface to the bottom. Assuming steady-state conditions, the first term in (1) can be neglected. The measurements of h were made at the ends of the pond, so we take the average of the remaining terms over the entire length, L:

$$\frac{1}{L}\int_0^L \frac{\partial}{\partial x}\int_0^{H+h} u^2 dz dx = -\frac{g}{L}\int_0^L (H+h)\ \frac{\partial h}{\partial x} dx + \frac{1}{\rho L}\int_0^L (\tau_s + \tau_b)\, dx\,. \tag{2}$$

Here L refers to the distance between the points at which h is observed, which in the present experiments was slightly less (220 m) than the actual length, l, at the surface (240 m). So long as the bottom profile is symmetrical, the only requirement is that these points be at equal distances from the ends so that (2) will apply. Under these circumstances, the advection term vanishes and, provided $H \gg h$ and H does not vary with x,[2] we have

$$0 = -\frac{gH}{L}(h_0 - h_L) + \frac{\bar{\tau}_s + \bar{\tau}_b}{\rho}, \tag{3}$$

with the bars designating average values over the length of the pond. Henceforth the bars will be omitted. If the setup, S, is defined as the difference in elevation between the two ends of the pond, the equation relating the average slope to the surface stress, τ_s, is simply

$$\frac{S}{L} = \frac{n\tau_s}{\rho g h}, \tag{4}$$

where n is defined as

$$n - 1 = \tau_b/\tau_s\,. \tag{5}$$

It is significant that equation (4) involves no assumptions regarding the distribution of stress within the fluid, nor does it predict the velocity distribution. The surface stress is known only to the extent that the bottom stress is known.

Only in the special case of laminar flow can n be determined explicitly, for then

$$\tau = \mu \cdot \partial u/\partial z\,. \tag{6}$$

Inserting this value for τ in the unintegrated equation of horizontal motion, neglecting the inertial terms, and assuming steady flow, one obtains (Keulegan, 1951)

$$\frac{d^2u}{dz^2} = \frac{g}{\nu}\frac{dh}{dx}, \tag{7}$$

where μ and u are the kinematic and dynamic viscosities respectively.

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[2] If H is not uniform, one must, as in the theory of seiches (Defant, 1925), regard H as the mean depth, equal to the total volume of water divided by the surface area. But actually, a convenient and practical method of obtaining this depth is to observe the period, T, of the fundamental seiche and, using the mean length, $\bar{l}$, at the surface in the direction of the wind, compute it from the formula $H = 4|\bar{l}|^2/gT^2$. This method applies only to basins of simple shape. As an example, we consider the data obtained for the model-yacht pond on December 5, 1951, when the observed depth over 90 % of the area was 240 cm. By the first method $H = 2.75 \times 10^4\text{m}^3/1.51 \times 10^4\text{m}^2 = 1.83$ m; and by the second method, with $\bar{l} = 240$ m and $T = 112$ sec, we obtain $\bar{H} = 1.85$ m. It is apparent that shoaling at the boundaries significantly effects the average depth.

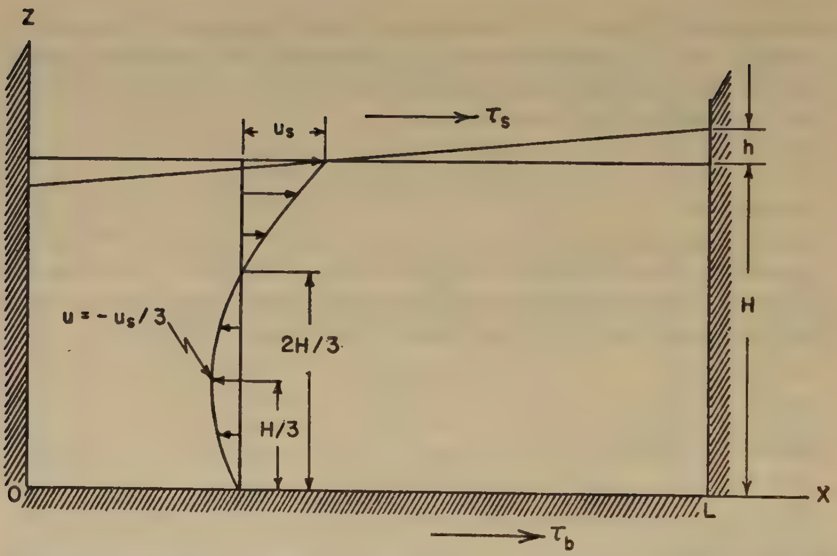


Figure 1. Longitudinal section of a rectangular channel to show the slope of the free surface under the action of the windstress, τ_s, and the velocity distribution within the water when the flow is laminar.

This relation can be integrated directly, in view of the requirement that the net flow through any cross section be zero. The results are:

$$\frac{dh}{dx} = \frac{6\nu u_s}{gH^2}, \tag{8}$$

and

$$\tau_s = -2\tau_b = 4\mu u_s/H, \tag{9}$$

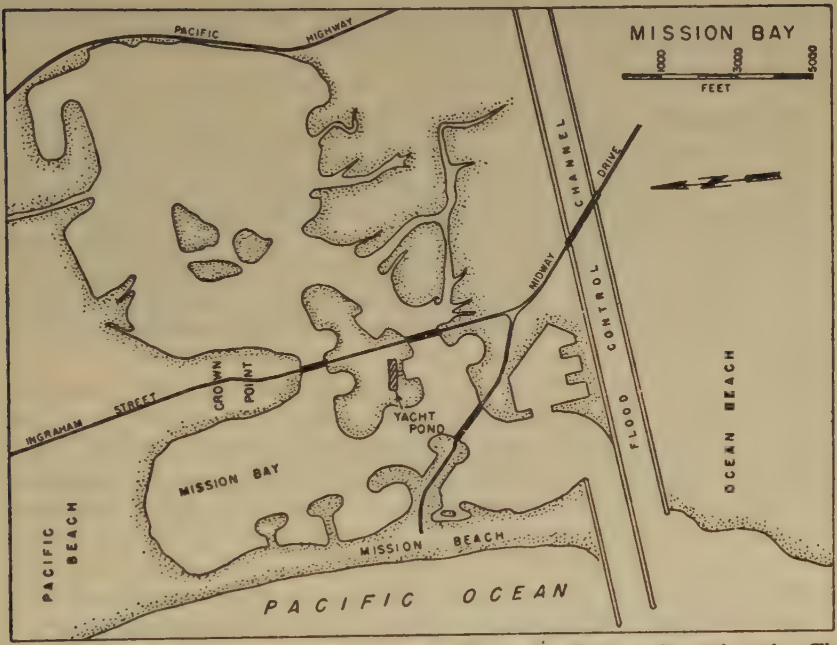
where u_s is the surface current speed. Then, because of (5),

$$n = 3/2. \tag{10}$$

The law for the velocity distribution within the fluid is given by the relation

$$u = u_s\left[3\left(\frac{z}{H}\right)^2 - 2\frac{z}{H}\right] \tag{11}$$

and is illustrated in Fig. 1. The flows consist of a surface current in the direction of the wind that extends down to one-third the depth and beneath it another current flowing in the opposite direction having a minimum value $u = -u_s/3$ at two-thirds the depth. The bottom stress is one-half the surface stress.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INGRAHAM
STREET
YACHT
POND
MISSION BAY
PACIFIC
BEACH
MISSION
BEACH
PACIFIC OCEAN

Figure 2. The Mission Bay model-yacht pond, site for the experimental work. The prevailing wind blows from the west.

When the flow is turbulent, however, the distribution of velocity is known to differ widely from that predicted by the laminar solution, hence the stresses τ_b and τ_s cannot be explicitly determined in terms of easily measurable quantities. Hellstrom (1941), by means of the Boussinesq theory of turbulence and on the basis of analogy to the empirical laws of the turbulent flow in open channels, proposed that, in general, the limits of the parameter n in (4) are $1.0 < n < 1.5$. In the present experiments a special investigation was undertaken to measure the bottom stress directly, and it was established that $\tau_b \lesssim 0.1\, \tau_s$, which is less than the threshold sensitivity of the instrumentation. Hereafter it will be assumed that $n = 1.0$ in all cases.

EXPERIMENTAL PROCEDURE AND INSTRUMENTATION

The site for the experimental work was a model-yacht pond situated on an island near the geometric center of Mission Bay, adjacent to San Diego (Fig. 2). The pond is roughly rectangular with dimensions approximately 240 x 60 x 2 m, and with the depth controllable over a total range of about one meter by a check-valve system in the 30″ pipe which connects the pond to the bay. The pond, constructed with its long axis parallel to the direction of the prevailing wind from the ocean, is separated from the Bay by about 50 m of sand with a maximum elevation of two m above the water surface.

The Wind and Temperature Measurements. Throughout the experiments the wind velocity and direction at 10 m elevation above the pond were continuously recorded with a three-cup Bendix anemometer mounted on a staff above the roof of a building adjacent to the pond. Thus the fetch for this anemometer was over smooth sand rather than over water. While it might be expected that the presence of the building would modify the air flow, the *relative* values of these windspeeds as compared to those measured at lower elevations over the pond were extremely consistent.

The wind velocity was also measured at elevations of 25 and 100 cm by two "Davis" propeller-type anemometers mounted on a staff at the downwind water's edge; photographs were taken at five-minute intervals. All three anemometers were calibrated together against a new Bendix "Aerovane" anemometer, for which a National Bureau of Standards calibration was supplied by the manufacturer. The four instruments were mounted on a staff at 10 m elevation and were allowed to run for 10 hours; the readings were averaged over five-minute intervals.[3] The results indicated that it would be necessary to apply a correction to the readings of the two Davis anemometers, but the ratios of the indicated windspeeds were consistent within 4%. Throughout the experiments all wind data were reported to the nearest 0.1 m/s, although this accuracy was considered to be somewhat optimistic at the higher windspeeds.

In conjunction with the wind measurements at the lower elevations, the air temperature at one and seven meters was read from shielded thermometers every 15 minutes to the nearest 0.1° C. Although transient temperature fluctuations of as much as 0.3° C often occurred at both elevations, the instantaneous difference in temperature (upper minus lower) was consistently about − 0.1° C. In addition, the water temperature was taken from a bucket sample. Throughout the tests the water was invariably warmer than the air; the average value for all readings (principally daytime) was 0.9° C, the maximum difference 2.6° C.

The uniformity of the wind field over the pond as well as the temperature homogeneity of the water assumed in the basic theory were investigated separately, and it was found that the observed departure from the assumed conditions was so small that the errors thus introduced in the final results could be neglected (Van Dorn, 1952).

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[3] From previous studies this procedure appears to be preferable to a calibration in a wind tunnel, where the gustiness is quite different from that found under natural conditions.

The Measurement of Setup. In the present experiments, each reported value for the setup, S, was actually the height of the column of water which corresponded to the difference in pressure at two points 220 m apart at equal elevations near the bottom of the pond and at equal distances from the ends. Because the vertical water velocity, w, can be expected to be greatest near the ends of the pond, it appears desirable to estimate the error introduced into the pressure measurements by neglecting it. Assuming a steady state and noting that $u = 0$ at the ends, the vertical equation of motion can be written

$$w \frac{\partial w}{\partial z} = - \frac{1}{\rho} \frac{\partial p}{\partial z} - g \, , \tag{12}$$

where p is the total pressure within the fluid. Integrating (12) between the bottom and the elevation, z', at which the pressure was measured, we obtain

$$p = p_a + \rho g z' - \tfrac{1}{2} \rho w^2 \, . \tag{13}$$

Ignoring the atmospheric and hydrostatic pressures, the difference in pressure, Δp, at the two ends of the pond due to the velocity will be

$$\Delta p = - \rho w^2 \, . \tag{14}$$

Taking a conservative value of $w = 1$ cm/sec, the pressure error amounts to only 1 dyne/cm^2, which is only one-tenth the minimum reported pressure during the experiments.

A block diagram of the instrumentation used to measure the pressure difference is shown in Fig. 3. A ¼″ diameter plastic tube, filled with distilled water and laid down the long axis of the pond, terminated at each end in a pair of pie tins clamped together and supported 55 cm above the bottom on a small tripod. Between the pie tins a thin, limp plastic membrane prevented the sea water from entering the tube and yet maintained adequate pressure continuity in the system. The outer tin contained a screened opening to prevent fouling of the membrane by marine organisms. In the center of the tube there was a Statham (Model 0.2-D) differential pressure gauge in an oil-filled plexiglass case; two additional membranes separated the oil from the distilled water in the tube. The Statham gauge is essentially a pressure-sensitive electric strain-gauge of the resistance-bridge type that produces a change in the direct current across the bridge which is proportional to a difference in pressure between its two pressure connections. The change in fluid capacity corresponding to full-scale

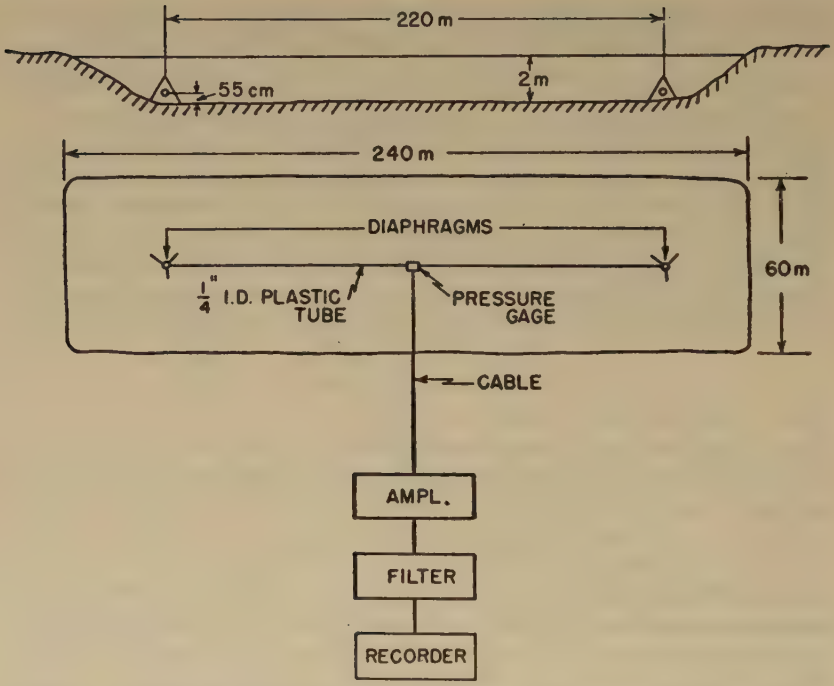

Figure 3. Block diagram of the instrumentation used in measuring the slope of the surface. The tripods supporting the pressure diaphragms were located approximately 10 m from the ends of the pond at the point where the depth became constant.

pressure differential is only about 0.16 cm^3, so that almost no flow took place within the tube.[4] Hence, the amplitude response of the system was virtually unity and the phase shift was zero for the frequencies encountered in the experiments (Iberall, 1950). In view of the low pressure levels experienced during the measurements, it was necessary to reduce the thermal response of the transducer to diurnal temperature fluctuations by burying it in the sand beneath the bottom of the pond.

The electric cable from the transducer ran to a building adjacent to the pond, where the signal was fed to a Micromax recorder through a D. C. amplifier and a long-period resistance-capacitance filter. The filter was designed for the multiple purpose of obtaining an electric impedance match between the amplifier and recorder, eliminating the surface waves from the record, and attenuating the seiche (period 112 sec).

[4] The volumetric distension of the tube under the pressures encountered was separately checked and was negligible.

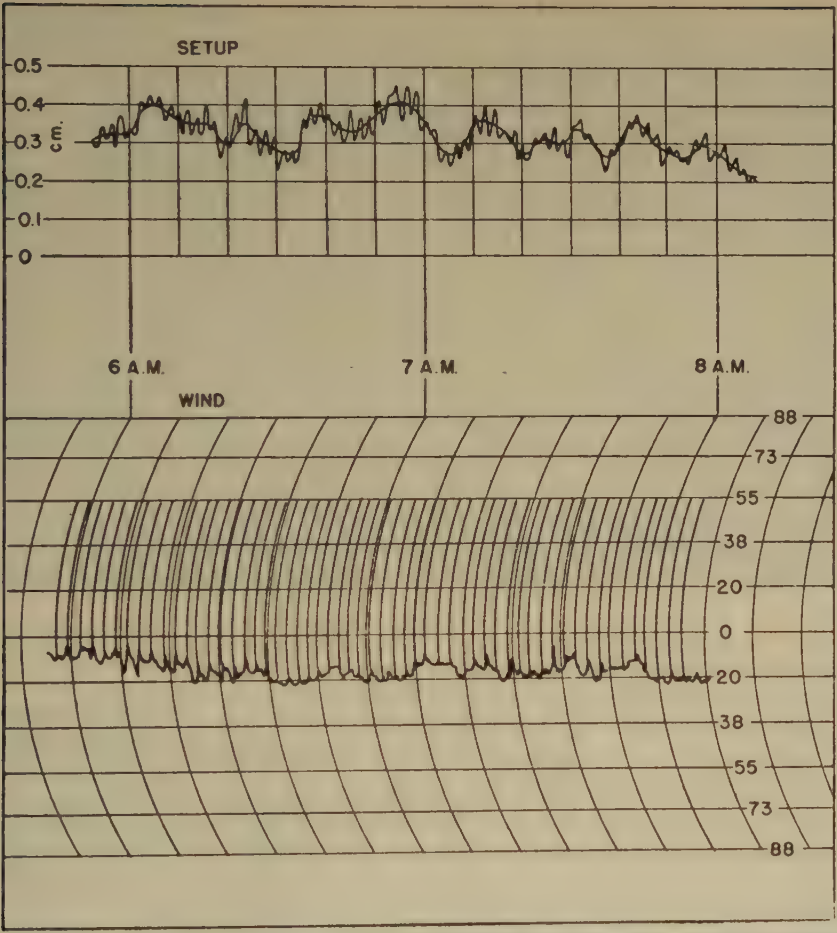

Figure 4. Typical records for setup and windspeed and direction at 10 m elevation. Windspeed is given by the frequency of the pips representing miles of wind, and the direction is in degrees from the axis of the pond. The sample is reproduced from an original record made on March 1, 1952.

Preliminary calibration of the instrumentation was made in a tank, where it was found that variations of the water level were reproducible within 0.01 cm of water. Throughout the actual tests the elevation difference between the two ends of the pond was read to 0.01 cm, which corresponds to a slope, S/L, of approximately

$$\frac{S}{L} = \frac{0.01}{2.2 \times 10^4} \doteq 5 \times 10^{-7} . \qquad (15)$$

Fig. 4 is a reproduction of a typical setup record and corresponding wind record at 10 m elevation. The seiche is plainly visible in the setup record even though it is attenuated by the filter to about 16% of its true amplitude. The reported value of the setup was obtained by drawing a line through the midpoints of the seiche oscillations and by integrating the area between this line and the zero-reference line over 20 minute intervals. The windspeed record was averaged over the same intervals.

The Bottom Stress Observations. The instrumentation for the bottom stress measurements was essentially identical with that used in the slope studies. However, instead of the pressure transducer and water-filled tube, the sensing element consisted of a circular plexiglass disk having an area of 1000 cm² which was suspended in the center of circular surround faired into the bottom at the approximate geometric center of the pond. The disk was supported at one edge by a pivot and was linked at the opposite edge to a Statham G-7 (Model 0.15–320) force transducer, the axis of suspension being perpendicular to the long axis of the pond. The surface of the disk was coated with a layer of pond sand embedded in cement to reproduce as nearly as possible the actual bottom roughness. Calibration of the unit was carried out in a tank by applying horizontal forces to the center of the disk with a torque arm in 0.1 g increments and by varying the transducer bias at each force level until a graph of sensitivity versus bias for each force increment was obtained. This was done so that the sensitivity could be adjusted in the field if the signals proved to be larger or smaller than anticipated. In the experiments the sensitivity was set at 10 g equal to full scale on the speedomax recorder, corresponding to a stress of 10 dynes/cm². The system had threshold accuracy of 0.01 dynes/cm², although it was found that the background noise (principally due to surface waves) was roughly ten times this amount.

SUBSIDIARY OBSERVATIONS

The Effect of Detergent. Keulegan (1951) discovered that waves in his experimental channel could be virtually eliminated by adding a detergent to the water. In this way the setup produced in the presence and absence of waves could be studied separately under nearly identical wind conditions. The same technique was successfully applied to these experiments with "Merrill's Rich Suds," a powder dispensed in pound packages. The detergent was scattered by hand along the upwind end of the pond so that the wind dispersed it evenly over the surface. It was necessary to apply soap[5] continu-

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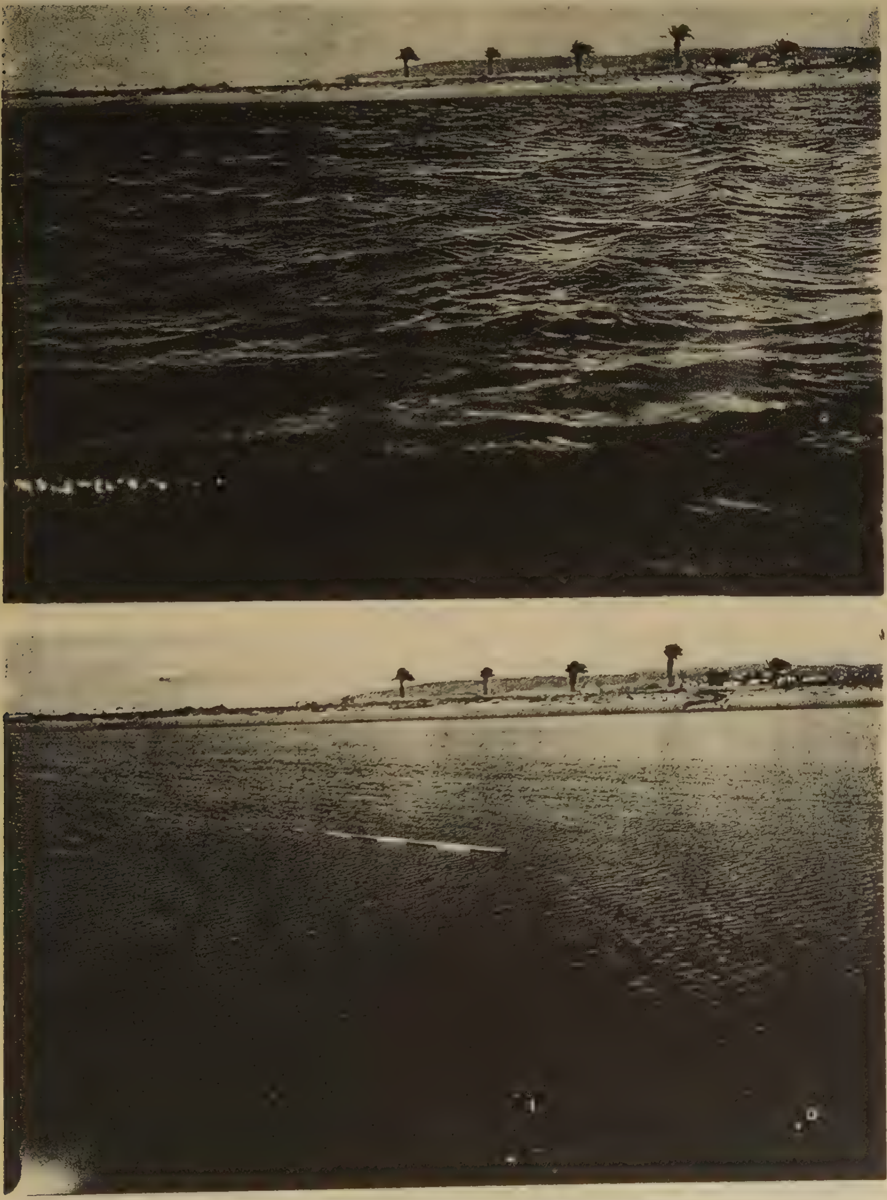
[5] Hereafter the terms "detergent" and "soap" are used interchangeably.



Figures 5 and 6. Two views of the downwind end of the pond taken at a wind-speed of 17 m/sec before and after the addition of detergent to the surface. The marker pole is graduated at one-foot intervals.

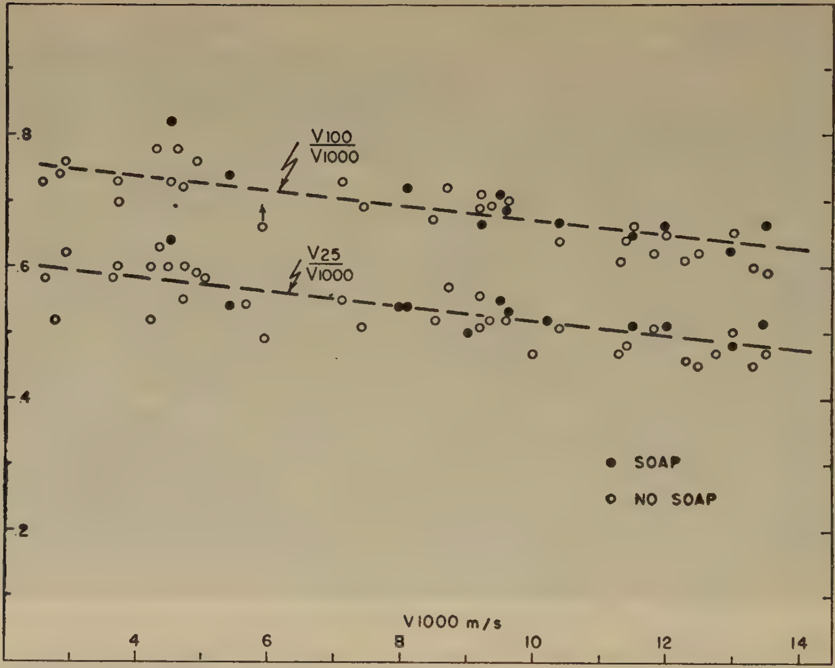


Figure 7. Ratios of the windspeed at elevations of 25 and 100 cm to that at 10 m as a function of the windspeed at 10 m.

ously as the wind drove the soap slick away from the scatterers and as incipient wave formation occurred. At the highest windspeeds, circa 15 m/s, this procedure required the combined efforts of three people running at top speed. Figs. 5 and 6 show the pronounced difference in the appearance of the water surface with and without detergent.

One might expect that the addition of detergent would also affect the flow of air over the water. The effect would be towards reducing the turbulence near the surface, thus increasing the wind at lower levels with respect to that at higher levels. The observations in Fig. 7 should reveal this tendency if present, but the scatter is too large to permit any conclusions except that the change is certainly not large.

An indirect but perhaps more precise method for estimating the effect of the detergent on the wind profile can be based on the observed increase of the velocity ratios (Fig. 7) with a decrease in windspeed (hence stress). For example, according to Fig. 13, for V = 12m/sec, the addition of detergent decreases the stress by an amount equal to a decrease in wind to 10.3 m/sec. The corresponding decrease in the velocity ratio in Fig. 7 is from 0.65 to 0.67, or 3%.

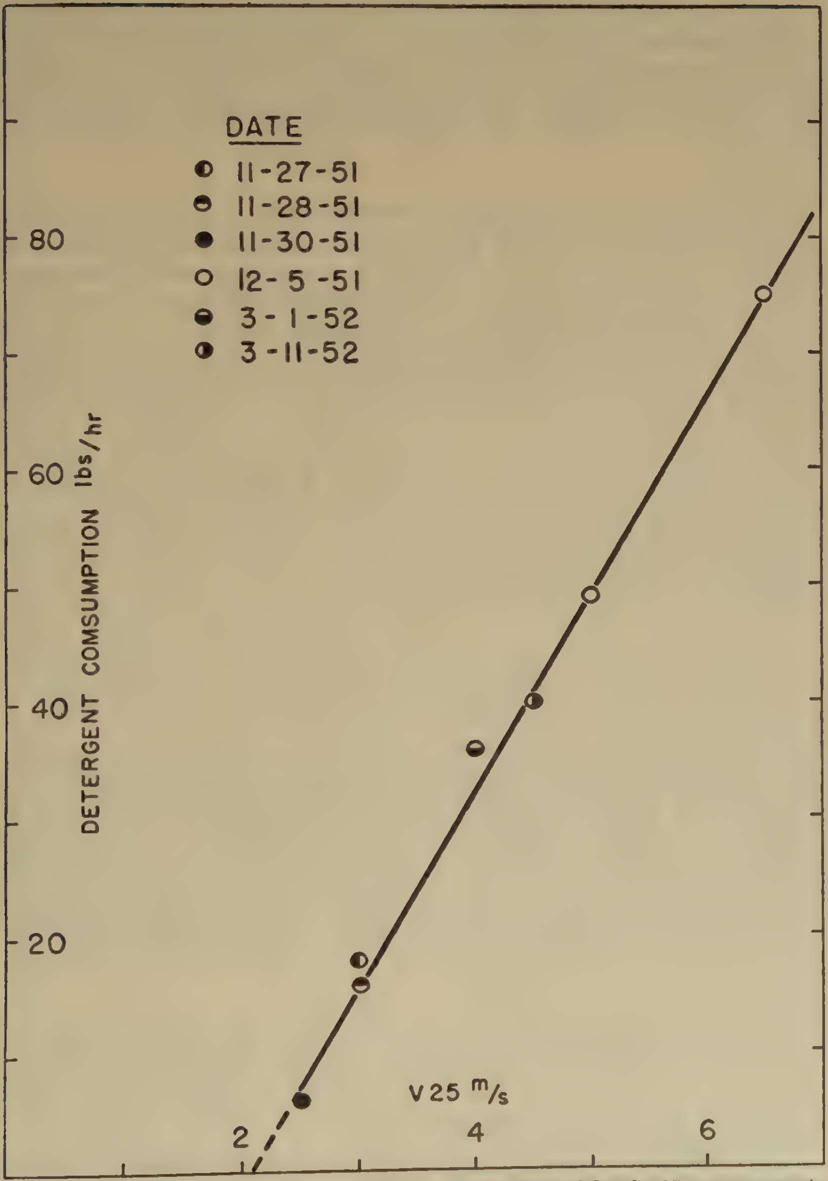


Figure 8. Detergent requirements as a function of windspeed for the 25 cm anemometer elevation. The data indicate the average rate at which detergent was dispensed in order to prevent the formation of waves on the surface.

Each time the soap technique was employed a record was kept of the total amount of soap consumed, and the results are shown in Fig. 8. The distribution of points is approximately linear and has an intercept at $V = 2$ m/sec. Since the soap was used only sparingly to prevent wave formation, this suggests that no waves occur at this windspeed.

Wave Observations. Additional evidence to support the above view was provided by a series of 40 low-angle photographs of the water surface taken at one minute intervals on a morning when there was a very low intermittent breeze. The windspeed was recorded at 25 cm elevation and was averaged over the same intervals. The water retained its glassy-calm appearance up to $V = 110$ cm/sec; incipient rippling in patches occurred from 110 to 200 cm/sec; but the surface became only uniformly covered with persistent wavelets at speeds above 200 cm/sec. Because of the large vertical gradient of the wind velocity at low elevations, no comparison is attempted between this value and those reported elsewhere in the literature; however, we can state that it falls between values reported by Jeffreys (1925) and those by Keulegan (1951) and Francis (1951).

Actually, close study of the surface indicated that it was at no time perfectly smooth under the least breath of wind; its appearance seemed to undergo a series of transitions with increasing windspeed. One point of similarity is remarkably consistent: at all winds one had the impression that, in contrast to the conventional concept of waves advancing before the wind, there were instead two sets of waves to the right and left of the wind direction. Moreover, the angle between the wind direction and the direction of wave travel appeared to depend on the windspeed, being initially about 75° and decreasing to a minimum of about 15° at the highest winds observed. During low winds, the intersections of corresponding wave phases traveled downwind at a much faster rate than those of the individual crests and, due to slight irregularities in wave length, they gave the surface a curious streaky appearance.

Current Measurements. By timing the drift rate of small flakes of paraffin wax, Keulegan (1951) made numerous measurements of the surface water velocities, in which the depth, H, and the viscosity, v, were varied separately for several windspeeds. His results are shown in dimensionless form by the curve in Fig. 9, where the windspeed was taken as the mean value in the laboratory channel. Because of dimensional considerations (see p. 271), the current measurements made throughout the present tests can be compared with those

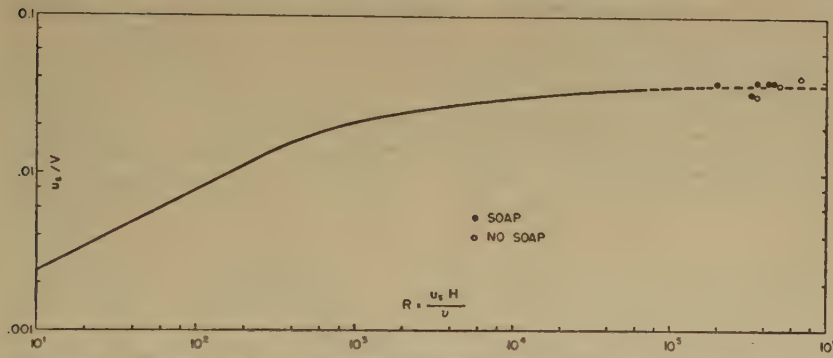


Figure 9. The ratio of surface current velocity to windspeed as a function of Reynold's number for the model-yacht pond, compared with the empirical curve obtained by Keulegan in a laboratory channel.

obtained by Keulegan;[6] these are shown in Fig. 9 by the cluster of points in the vicinity of $R = u_s H/\nu = 10^6$. Since both series of measurements were made with and without soap, the close agreement between the points obtained here and the empirical curve obtained by Keulegan supports his conclusion that the magnitude of the surface current is unaffected by the presence of waves and is independent of depth at large Reynold's numbers.

THE EXPERIMENTAL RESULTS OF THE STRESS MEASUREMENTS

Setup Versus Windspeed. Measurements of setup and windspeed were made from November 1951 through March 1952 under a variety of weather conditions. From more than 300 hours of recordings, only those for which the wind direction was within 20° of the pond axis (a total of about 60 hours) were considered acceptable for analysis. All of the data for the 10 m wind elevation are shown in Fig. 10. The analogous representations for the two lower anemometer elevations are not given, but they are similar except for the scale of the windspeed. The points obtained when the surface was covered with soap tend to fall along a straight line through the origin, while those taken when waves were present initially follow the same line but diverge upwards as the wind increases.

The Scatter of the Data. In Fig. 11 we have plotted the recorded seiche amplitude (16% of actual amplitude) against windspeed, with and without soap. It will be noticed that with soap on the surface the

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[6] The floats used in the present tests had a diameter of 1″ and were cut from cork composition (0.050″ thick) having almost neutral buoyancy.

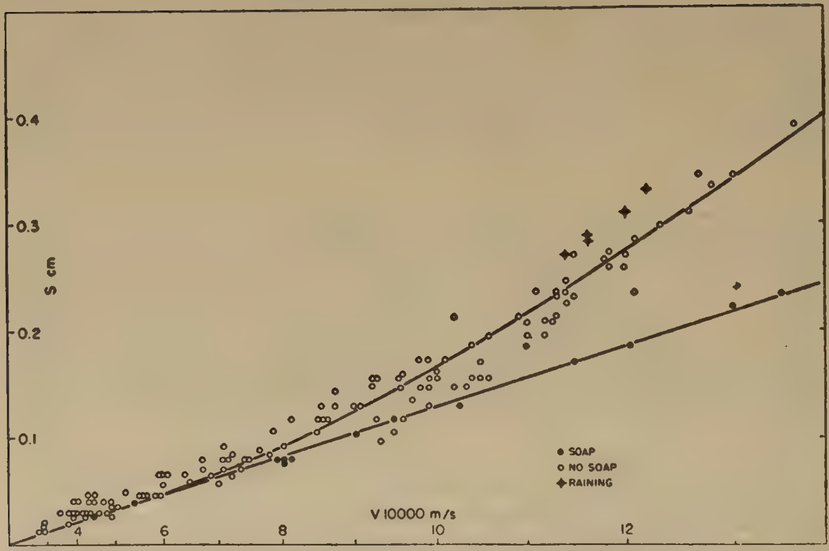

Figure 10. Original data for setup as a function of windspeed at 10 m elevation. The smooth curves were drawn by inspection. Each point is a 20-minute time average for both wind and setup.

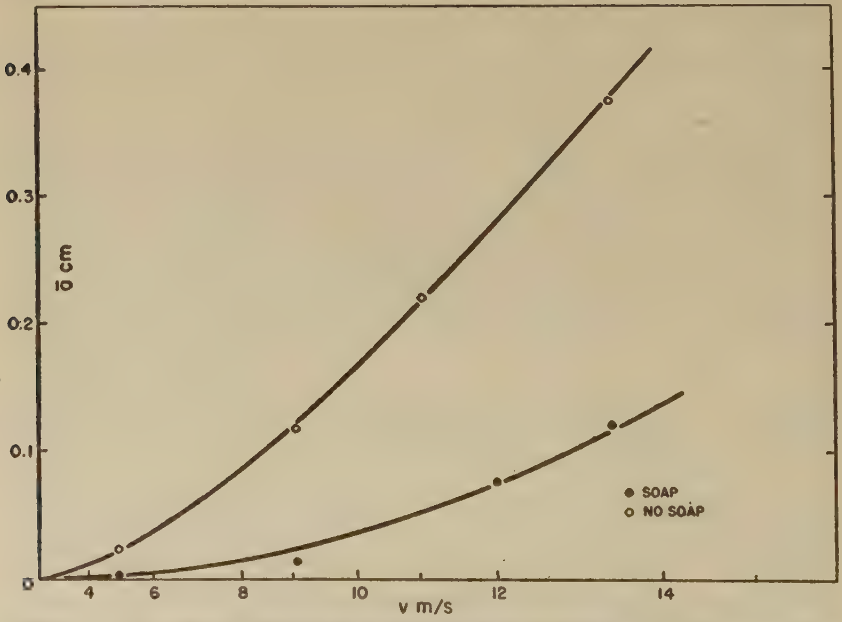

Figure 11. Recorded double-amplitude of the seiche as a function of windspeed at 10 m elevation. Each point represents the mean of two groups of 10 seiche cycles at the average windspeed over the same time interval.

seiche is reduced by a factor of three, approximately. In Fig. 10 it can be seen that the scatter of data is similarly reduced by the addition of soap. Furthermore, the seiche amplitude equals approximately the scatter of setup values for any fixed windspeed. Hence one might be inclined to ascribe the scatter to error in measuring setup as related to seiche activity. But this error was previously shown to be only of the order of 0.01 cm, and thus it cannot account for the observed scatter.

Another possibility is that the scatter may be related to the gustiness of the wind. For any given setup the scatter in windspeeds in Fig. 10 is of the order of 10% of the mean speed. This ratio is by no means excessive. From this point of view the seiche activity can be considered a result of gustiness. The reduction in seiche amplitude produced by soap implies that the addition of soap to the surface significantly reduces the gustiness of the wind in the lower layers. Further study is indicated.

The Transient Response of the Pond. Because the theory of surface slope assumes that a steady-state must be established, the transient response of the pond to changing wind force was examined in some detail. Haurwitz (1951), in a theoretical analysis of a rectangular basin, concluded that equilibrium will be obtained in a time of the order of one seiche period, although oscillation about the equilibrium level may persist, depending on the internal and bottom friction.

The passage of a cold front during the night of March 1, 1952 permitted an experimental examination of the transient response. Within about three minutes the wind changed direction abruptly from south to west and quadrupled in intensity. Shortly thereafter there was a sharp decrease in windspeed, followed by a subsequent oscillation of lesser magnitude. At the highest windspeed (nearly 20 m/sec) the close spacing of the mile-pips on the wind record permitted an accurate determination of the rate of change of windspeed. In Fig. 12 the observed setup is compared to the steady-state value obtained from the curve in Fig. 14 by inserting the appropriate observed windspeed. Even in this extreme case the amplitudes of the two curves correspond closely, and the phase lag is never more than two seiche periods (about 4 min.). Hence, the response-time was much more rapid than the 20 minute averages to which the data were customarily reduced.

The Bottom Stress. Nearly 100 hours of bottom-stress recordings were made over a range of windspeeds up to 10 m/sec (at 10 m elevation). The recorder pen always drew a nearly straight line on the chart, hence no conclusive variation of bottom stress with windspeed could be established; it can be stated only that within the accuracy of

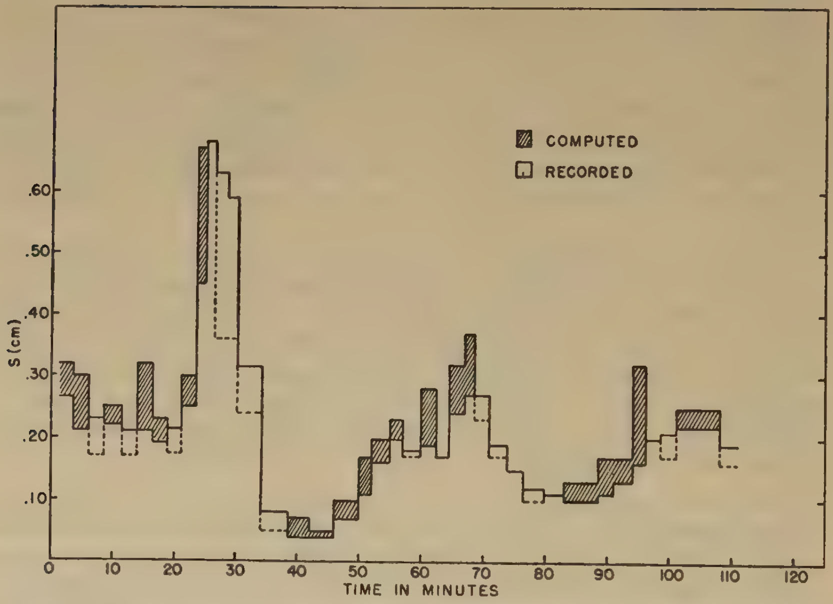

Figure 12. The transient response of setup to changing windspeed. The observed setup was averaged over the time interval corresponding to each mile-pip of the wind record. The computed setup was taken from Fig. 14 for a wind average over the same time interval. The dotted lines indicate when the computed setup was less than the observed setup.

the instrumentation (0.1 dyne/cm^2) the stress was negligible. This conclusion is supported by the observations of divers with underwater swimming equipment. They reported that sediment clouds stirred up from the bottom remained sensibly stationary for several hours and that no motion of the long sparse grasses growing upwards from the bottom could be detected. In the course of a few days, sufficient marine growth and sediment would accumulate on the surface of the sensing disk to unbalance it, and the record would gradually drift off to one side of the initial zero. With the long-period filter switched out of the recording circuit, oscillations in the record had a period roughly the same as the longer surface waves (1–2 sec.) and amplitudes of the order of 0.3 dynes/cm^2 together with barely perceptible modulations of seiche period (112 sec.). It is hoped that the experiments can be continued later in the year with the advent of higher winds, but meanwhile we conclude tentatively that the bulk of circulation within the pond is confined to a relatively thin layer near the surface.

INTERPRETATION OF THE RESULTS

An Empirical Law for Setup. Keulegan (1951) proposed that the total setup observed in the laboratory channel was actually the combination of two effects: first, the frictional drag on the water surface, which is present at all windspeeds; second, an additional effect attributed to wave development, which commences only after the wind has reached a certain value, V_c, which he defined as the "formula" velocity. He also found that the second effect could be indefinitely postponed in terms of increasing windspeed either by adding detergent to the surface or by adding sugar to the water to increase its viscosity. In addition, the ratio of surface current to windspeed, u_s/V, at high Reynolds numbers is observed to be constant and unaffected by the addition of soap. It appears, therefore, that such a partition of the setup has a real physical basis and is not due to some special action of the soap in "greasing" the water surface.

Keulegan's results can be represented by the following equations:

$$S_1 = aV^2\,, \qquad S_2 = b(V - V_c)^2\,, \qquad (16a, b)$$

where S_1 and S_2 are the partial setups due to friction and waves, respectively, and

$$S = S_1 \text{ for } V \leqslant V_c; \qquad S = S_1 + S_2 \text{ for } V > V_c\,. \qquad (17a, b)$$

With soap on the surface, (17a) holds for all windspeeds. From dimensional considerations he proposed that

$$a = \frac{AL}{gH}\,, \quad b = \frac{BL}{gH}\sqrt{\frac{H}{L}}\,, \qquad (18a, b)$$

where A and B are dimensionless constants for any given set of wind measurements. However, a question is raised here concerning the validity of the factor $\sqrt{H/L}$ in (18b). In view of equation (4), this would imply a secondary dependence of wind stress on depth. Moreover, Keulegan's experimental determination of the dependency of S_2 on H is not conclusive, and the secondary dependence on L was arbitrarily assumed for dimensional consistency. We propose, instead,

$$a = \frac{L}{gH}\alpha^2\,, \quad b = \frac{L}{gH}\beta^2\,. \qquad (19a, b)$$

In order to determine whether or not the empirical results obtained in the present experiments agree with the form proposed by Keulegan, it was necessary to evaluate the quantities α, β and V_c for each anemometer elevation. The coefficient α was determined from the slope of

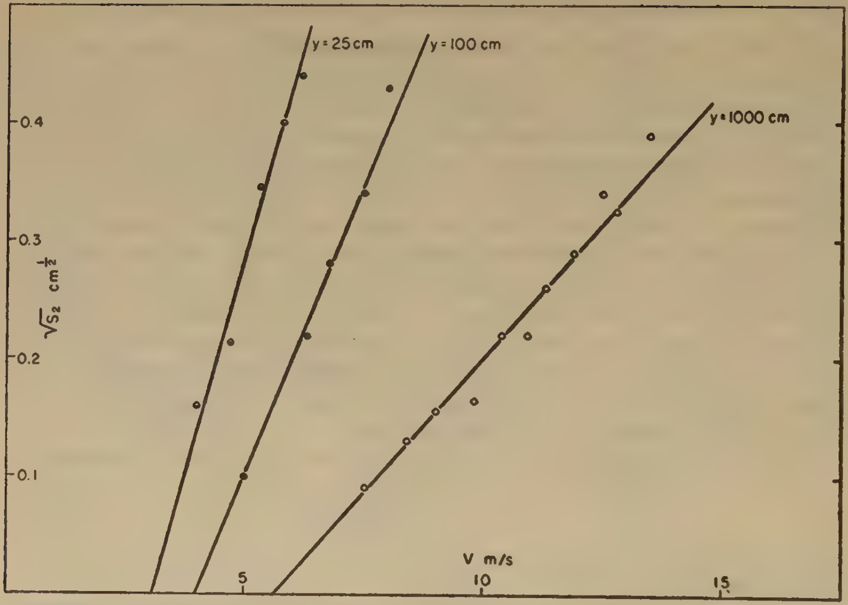

Figure 13. Square root of the additional setup, S_2, associated with waves as a function of windspeed.

the straight line giving the best fit to the points obtained when the surface was covered by soap, using equations (16a) and (19a). The data for total setup were then averaged over convenient class intervals of windspeed, and a mean value for S_2 for each class interval was obtained by subtracting the ordinate beneath the same straight line at the mean square windspeed within the interval. In Fig. 13, the square root of S_2 is plotted against windspeed for each anemometer elevation. The straight lines through the points were drawn to give a best fit to the points, weighting each point according to the number of data within the interval. The intercepts at $S_2 = 0$ were construed to be the most reasonable values of V_c, and the slope of the lines gives the coefficient β by virtue of (16b) and (19b). The coefficients α and β and the formula velocity V_c determined by the above procedure for each anemometer elevation are given in Table III together with the corresponding values obtained by Keulegan. Using the values of the three parameters given in Table III, the curves of Figs. 14, 15 and 16 were computed. The agreement with the observed data is satisfactory.

It will be noticed that the values obtained by Keulegan in Table III fall between those obtained for the model-yacht pond at the 25 and 100 cm anemometer elevations, being nearer the latter values. This "equivalent height" is considerably higher than the actual height (about 10 cm) at which the wind was measured in the laboratory channel. This result is in contrast to Keulegan's conclusion that the walls and ceiling of his channel imposed no significant restriction on the air velocities.

TABLE III. COMPARISON OF THREE EMPIRICAL PARAMETERS FOR THE MODEL-YACHT POND AND LABORATORY CHANNEL

Anemometer elevation (*cm*)	α $\times 10^3$	β $\times 10^3$	V_c (*m/sec.*)
25	2.1	4.6	3.1
100	1.7	3.2	4.0
1000	1.1	1.5	5.6
Keulegan	1.8	3.7*	3.9*

* Average for five water depths

The Relation Between Wind and Surface Current. If a Reynolds number is defined as $R = u_s H/\nu$, then the curve in Fig. 9 can be approximated by the expressions

$$\frac{u_s}{V} = K_1 \sqrt{\frac{u_s H}{\nu}} \text{ for } R \ll 10^3 \tag{20}$$

and

$$\frac{u_s}{V} = K_2 \text{ for } R \gg 10^3 \,, \tag{21}$$

where K_1 and K_2 are constants which depend only on how the wind is measured. The influence of the viscosity in (20) led Keulegan to suppose that the entire distribution of velocity within the water might be laminar at low Reynolds numbers. Combining (20) and (8), the theoretical equation for surface slope under laminar conditions, we find that

$$\frac{dh}{dx} \doteq \frac{S}{L} = 6K_1^2 \cdot \frac{V^2}{gH} \tag{22}$$

is the condition to be satisfied for $R \ll 10^3$. But (22) has the same form as (16a); moreover, Keulegan was able to demonstrate that $6K_1^2 = \alpha^2$ and thus verify his assumption. For larger bodies of water, such as that considered here, the Reynolds number will always be much greater than 10^3 for any observable surface slopes, and consequently the flow is turbulent. One would therefore expect the results of the present current measurements to obey the law given by (21). While the scatter of individual measurements has a standard deviation of 8%, there is no significant variation in the ratio u_s/V with a fourfold increase in Reynolds number.

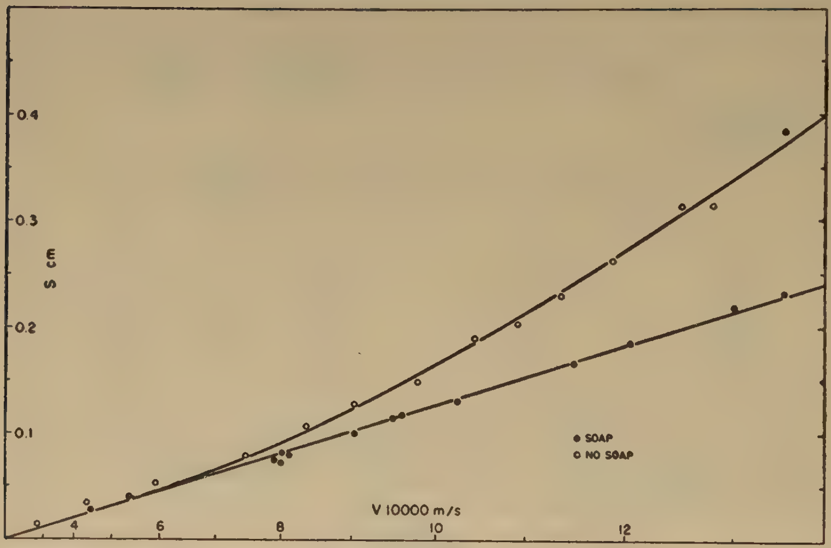

Figure 14. Setup as a function of the square of the windspeed at 10 m elevation. The curves were computed from equations (21) and (24).

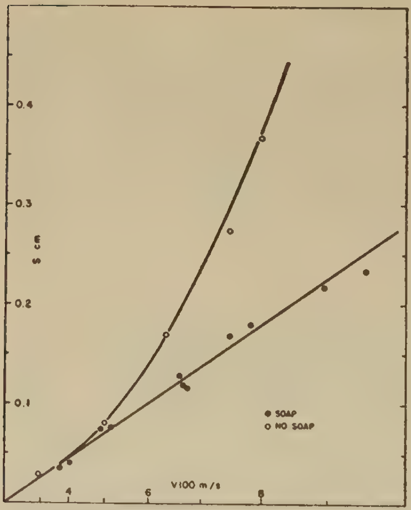

Figure 15. Setup as a function of the square of the windspeed at 100 cm elevation.

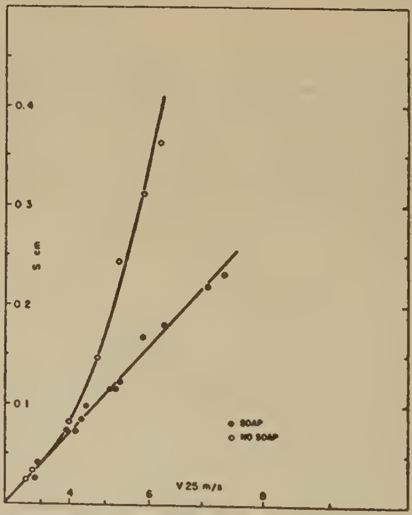

Figure 16. Setup as a function of the square of the windspeed at 25 cm elevation.

In attempting to relate the measurements in the pond to those in the laboratory channel, it was found that a systematic relationship exists between the parameters listed in Table III and the constant K_2 in (21). The four parameters α, β, $1/V_c$ and K_2 as obtained under natural conditions for the two lower anemometer elevations and the corresponding values obtained under laboratory conditions have nearly the same ratios (Table IV).

TABLE IV. The Ratios (Model-yacht Pond to Laboratory Channel) of Four Parameters

Anemometer elevation (cm)	α	β	$1/V_c$	$K_2 = u_s/V$
25	1.19	1.24	1.19	1.23
100	0.93	0.87	0.92	0.92
1000	0.62	0.40	0.66	0.62

The agreement for the highest anemometer is poor, which is not surprising in view of the fact that it was mounted above a building nearby rather than over the pond. It is significant that the discrepancy is greatest for β; i. e. when $V > V_c$. The values of u_s/V in Fig. 9 are for the 25 cm elevation and were divided by the factor 1.23.

The Formula Velocity. No obvious physical changes in the appearance of the water surface could be noted at the windspeed V_c. Waves appeared at lower windspeeds and grew in a regular manner as the wind increased through this range. It is instructive, however, to consider the stress, τ_s', and the surface current, u_s', which occur at the windspeed V_c. Since the Reynolds number is greater than 10^3, it follows from (21) that

$$\frac{(u_s')_P}{(u_s')_L} = \frac{(V_c)_P}{(V_c)_L} \cdot \frac{(K_2)_P}{(K_2)_L}, \tag{23}$$

where P and L refer to pond and laboratory. In view of the ratios in Table IV, this means that the surface currents in the pond and laboratory are equal at the windspeed V_c. Empirically, the numerical value for u_s' is approximately 12 cm/sec. It is concluded tentatively that the stress τ_s' is associated with a *specific* value of the surface current, independent of the scale of the experiment.

The Wind Stress with a Smooth Water Surface. Consider now the case when the water surface is smooth, defined by $V \leqslant V_c$. By combining equations (4) and (16a), we obtain a relation between the boundary stresses and the windspeed at a specific elevation

$$\tau_s = \rho\alpha^2 V^2. \tag{24}$$

Taylor (1916) has proposed that the surface stress can be represented in terms of a resistance coefficient, γ^2, defined by

$$\tau_s = \gamma^2 \rho_a V^2 , \tag{25}$$

where ρ_a is the air density. Comparing (24) and (25), the form of the latter is verified provided that

$$\gamma^2 = \frac{\rho}{\rho_a} \alpha^2. \tag{26}$$

As an example we consider the two extreme anemometer elevations, 25 cm and 1000 cm. Taking $\rho_a = 1.2 \times 10^{-3}$ and α from Table III, the corresponding values of the resistance coefficient are $\gamma^2 = 0.0037$ and 0.0011 respectively. Although the above figures apply only to smooth water conditions, their range encompasses all values reported by 12 different investigators, as compiled by Francis (1951). It is suggested that the variability in the height at which the wind is measured may be a contributory factor in the present ambiguity regarding γ^2 (Montgomery, 1951).

Wind Stress with a Rough Water Surface. If, by analogy to the smooth water case, we combine equations (4) and (16), we obtain a relation for the total stress when the surface is rough; defined by $(V > V_c)$,

$$\tau_s = \rho\alpha^2 V^2 + \rho\beta^2 (V - V_c)^2 . \tag{27}$$

The coefficients α and β depend only on where the wind is measured. To a first approximation, the above expression for the wind stress appears to be independent of fetch and hence independent of the size of waves which can develop. The form of (27) is incompatible with an abrupt increase in the stress at a "critical windspeed," as proposed by Munk (1947).

If it is recalled that the addition of soap to the surface at high windspeed produces no corresponding change in the surface current, it is evident that the resulting change in setup can be due only to a change in the character of the circulation *beneath* the surface. Qualitative support for this view is provided by observations of drifting objects. When the surface was covered with soap, a sharp gradient of velocity with depth was apparent. Small particles in the uppermost layer (circa 1 cm) traveled at roughly twice the speed of those a centimeter or so deeper, and there was little change in speed at all greater depths within which the trajectories could be followed. The motion was essentially steady and horizontal. In contrast, when the surface was rough, bits of paper which became waterlogged and sank rather slowly moved in sluggish vertical circles of about one foot in diameter in the direction of the wind, with a mean horizontal velocity roughly independent of depth. Since the virtual elimination of surface waves is the most obvious manifestation of the change in setup which takes place when soap is applied, it is suggested that the waves themselves, under the action of the wind, may be an effective agent in increasing the downward transport of horizontal momentum through the surface.

The Stress Due to Rainfall. If the original data in Fig. 10 are examined, it will be noticed that a group of five points giving the total setup in the vicinity of the windspeed $V = 12$ m/s lies consistently above all others. In attempting to resolve this anomaly in the records, it was discovered that this series of data was obtained in the early morning hours of March 12, 1952 during a period of heavy rain and that no rain had fallen throughout the remainder of the experiments. The rain gauge at Lindbergh Field, three miles away, recorded an average rate of rainfall of 0.25 inch/hour during the period in question, and it is thus possible to make an estimate of the order of magnitude of the stress due to the rain.

First it is necessary to estimate the reduction in the horizontal component of the velocity of a falling raindrop as it passes through the layer of slowly moving air near the surface. To simplify the problem we consider the coordinate axes to be moving at the windspeed, V_0, at an arbitrary elevation, z_0, with the z-axis positive downward. We assume that initially a raindrop has a horizontal component of velocity equal to that of the wind; therefore let u and V be the subsequent relative velocities of the drop and wind respectively, referred to the moving axes. We are interested in the final velocity, u_0, of the drop at a time, t. equal to that required for the drop to fall at terminal velocity, w, through the distance, z_0. The equation of motion is

$$m \frac{du}{dt} = F \,, \tag{28}$$

and we take:

$$F = \delta (V - u)^2 \,, \tag{29}$$

$$V = Kz \,, \tag{30}$$

$$z = wt \,, \tag{31}$$

where K is a constant. The assumed linear increase in relative windspeed permits a closed solution and gives a very conservative result. Combining these four equations,

$$\frac{du}{dt} = \frac{\delta}{m} (Kwt - u)^2 \,, \tag{32}$$

and, after integrating between the limits $u = 0$ at $t = 0$ and $u = u_0$ at t $= z_0/w$, the solution is

$$\frac{V_0 - u_0}{c} = \tan h\left(c \cdot \frac{\delta}{m} \cdot \frac{z_0}{w}\right), \tag{33}$$

where $$c = \frac{mKw}{\delta}, \quad V_0 = Kz_0 .$$

Expanding (33) in Taylor's series, we obtain the relation

$$\frac{u_0}{V_0} = \frac{1}{3} V_0 \frac{\delta}{m} \frac{z_0}{w} - \frac{2}{5} V_0^2 \left(\frac{\delta}{m} \cdot \frac{z_0}{w}\right)^2 \ldots, \tag{34}$$

which gives the ratio of the final horizontal velocity of the drop to the velocity at z_0. Assuming a spherical raindrop of diameter D and density ρ, the ratio δ/m is

$$\frac{\delta}{m} = \frac{\frac{1}{2} \rho_a C_d \left(\frac{\pi D^2}{4}\right)}{\frac{1}{6} \pi \rho D^3} = \frac{3}{4} \frac{\rho_a}{\rho} \frac{C_d}{D}, \tag{35}$$

where C_d is the drag coefficient. According to Spilhaus (1948), reasonable values for these variables with continuous heavy rain are $C_d = 0.2$ and $D = 0.6$ cm, and the appropriate terminal velocity is $w = 10^3$ cm/s. Again taking $\rho_a = 1.2 \times 10^{-3}$, we find that

$$\frac{\delta}{m} \doteq 3 \times 10^{-4} . \tag{36}$$

Combining (34) and (36) and taking only the first term of the series,

$$\frac{u_0}{V_0} \doteq 10^{-7} V_0 z_0 \ldots . \tag{37}$$

Assuming now the arbitrary values $V_0 = 12$ m/sec at 10 m elevation, we see that u_0 will be only 15% of V_0, or, in terms of a raindrop initially traveling with the wind and falling from a height of 10 m through a region of linearly decreasing wind, its horizontal velocity at the ground would still be about 85% of its initial value. Because the profile assumed is conservative, the change in u will be neglected in the following discussion.

We consider now the average horizontal stress, τ_r, acting at the water surface due to the horizontal momentum of the raindrops. We write

$$m \frac{du}{dt} = \frac{d(mu)}{dt} - u \frac{dm}{dt} = - \tau_r, \tag{38}$$

where u is now the horizontal velocity of the drops with respect to the surface. With steady rain, we neglect the term $d(mu)/dt$ and note that dm/dt is just the rate of rainfall. Assuming, as before, that $u = V = 12$ m/s at 10 m elevation, we have

$$\tau_r = u \frac{dm}{dt} = \frac{1.2 \times 10^3 \times 0.6}{3600} = 0.23 \text{ dynes.} \tag{39}$$

The corresponding setup as computed from equation (4) is $S_r = 0.035$ cm. This, when compared with the average of the five points taken from Fig. 10, which is roughly 0.04 cm, constitutes about 20% of the total effect. It thus appears as if heavy rainfall can considerably augment the stress due to the wind.

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MARINE GEOLOGY OF NORTHWESTERN PACIFIC: DESCRIPTION OF JAPANESE BATHYMETRIC CHART 6901

By Robert S. Dietz

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MARINE GEOLOGY OF NORTHWESTERN PACIFIC: DESCRIPTION OF JAPANESE BATHYMETRIC CHART 6901

By Robert S. Dietz

Abstract

This paper is a geological discussion of the northwest Pacific, to accompany the Japanese Hydrographic Chart 6901 (a bathymetric chart of the northwest Pacific) which is presented as Plate 1. A special edition of this chart was published under an arrangement made by the writer between the Japanese Hydrographic Office and The Geological Society of America in the belief that it will provide useful topographic data in a previously little-known portion of the sea floor and that it will stimulate further interest in Pacific marine geology. A comparison of the land surface with the sea floor, both of which are contoured at 500-m intervals, emphasizes the variety of sea-floor features and the grand scale of this submerged topography where erosional leveling is subdued.

The region covered by the chart can be divided into (1) the Pacific Basin proper, (2) the Philippine Sea Basin, including the arcuate ridges extending from Japan to Palau, and (3) the submerged portion of the Asia continental block, including the continental shelf and slope and the encompassed "intra-continental" basins. Large-scale undulations or swells and swales of low relief are the dominant structures of the Pacific Basin, but the five great groups of seamounts are the most striking features. A study of the original soundings shows some abrupt changes in level and grabenlike depressions which probably mark fracture zones in the earth's crust. The seamounts are considered to be volcanoes, many of which are capped with coral. Smooth bottom characteristizes most of the Basin, suggesting a thick sedimentary blanket. Two of the seamount groups (the Emperor Seamounts and the Magellan Seamounts) are entirely submerged; another group pierces the surface at only two places (Marcus I. and Wake I.); the Caroline and the Marshall-Gilbert groups form numerous atolls. A large number of the seamounts have deeply submerged flat-topped summits and, thus, are guyots or tablemounts. However, because of the low seismicity and the rarity of raised islands, the Pacific Basin is considered a stable area, and the sinking of the guyots is thought to be a local isostatic subsidence in response to the load of the seamounts.

The Philippine Sea Basin is bounded by the Asia continental block on the west and by the great geanticlinal ridges, extending from Japan to Palau, on the east. Trenches, presumably marking downbuckles in the earth's crust, lie seaward of these ridges. These geanticlinal ridges are active belts surmounted by volcanoes and a string of raised islands. The Kyushu-Palau Ridge, another large geanticlinal ridge, bisects the basin. Soundings give little evidence of guyots on any of the ridges or in the Philippine Sea. The Daito Mountains, nested between the Kyushu-Palau Ridge and the Ryukyu Trench, are probably orogenic rather than volcanic. The Philippine Sea Basin appears to be non-sialic and a region with normal Pacific crustal structure which has been deformed by the same compressional forces that have affected the margin of Asia.

The continental slope, marking the boundary of the Asia sialic block, extends from Kamchatka, along the Kurils, Japan, and the Ryukyus to Formosa, and probably along the east side of the Philippines. Extensive featureless shelves with shelf-breaks at normal depths fringe China and Siberia. The continental slopes are canyoned and irregular in detail. In the Okhotsk Sea there is a remarkable deep terrace which is probably a subsided normal shelf. The Kuril Basin, the Japan Sea Basin, and the Ryukyu Basin are similar abyssal pear-shaped basin within the continental framework. *En bloc* drifting of the associated island arcs, opening up simatic pools in the continental block, may account for these basins. Their smooth bottoms suggest that they are sediment traps for a great amount of sediment eroded from Asia.

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CONTENTS

TEXT

Page
Introduction 1200
Acknowledgments 1201
Construction of the chart 1201
General description 1202
  General 1202
  Deep-sea sediments 1203
  Faults on the sea floor 1204
Arcuate structures 1205
  General 1205
  Trenches 1205
  Honshu-Mariana ridges 1207
Seamount groups of the Pacific Basin 1208
  General 1208
  Emperor Seamounts 1209
  Marcus-Wake Seamount Group 1211
  Magellan Seamounts 1211
  Marshall and Gilbert Seamount Group 1212
  Age of the Pacific seamount groups 1212
Philippine Sea Basin 1214
Islands 1215
  General 1215
  Raised islands 1216
  Coral-reef problem 1216
Japan Sea Basin, Ryukyu Basin, and Kuril Basin as intra-continental basins 1217
Continental shelf and slope 1218
  Continental shelf sediments 1218
  Submarine canyons 1218
  Okhotsk Deep shelf 1219
  Depth of the shelf-break 1219
Suggestions for future work 1222
References cited 1223

ILLUSTRATIONS

Figure Page
1. Sounding profiles across trenches 1206
2. Some representative sounding profiles in the Northwest Pacific 1210
3. Sounding density chart 1213
4. Simplified depth chart and chart of shelf-break depths 1220
5. Major structural elements 1221
6. Isotherm and bottom-sediment chart 1222

Plate Facing page
1. Chart 6901: Bathymetric chart of the Northwest Pacific 1199*
2. Geology of the South Sea islands 1224

TABLES

Page
1. Sounding correction chart 1202
2. Data on Emperor Seamounts from Chart 6901 original soundings 1209

INTRODUCTION

This paper was prepared to accompany the Japanese Hydrographic Office's Chart 6901, *Bathymetric Chart of the Northwestern Pacific* which is presented as Plate 1. This chart shows, in greater detail than ever before, the geomorphology of about one-sixth of the Pacific Ocean sea floor—an area about three times as large as that of the United States. In the same manner that a topographic chart is a necessary prerequisite to geological work on land, an adequate bathymetric chart is a necessary precursor to the development of marine geology and geophysics. The configuration of the sea floor is the foundation upon which the future superstructure of the marine sciences will be raised. In 1939, Chart 6080, a chart similar to 6901 but based on fewer data, was published by the Japanese but, because of war-time conditions, only 100 copies were printed so that the existence of the chart was almost unknown to scientists inside as well as outside Japan. It is hoped that, by placing this special edition of this chart in the hands of earth scientists through the medium of this Bulletin, scientific consideration of problems of the Pacific sea floor will be greatly stimulated.

*in pocket at back of book

The writer has prepared the paper with the object of (1) making the chart more useful by indicating the method of construction, limitations of the sounding data, etc., (2) describing the salient features, and (3) presenting a few ideas concerning the marine geology of the region. At the outset, the writer planned mainly to present the Japanese point of view, but a search of the literature has revealed few papers concerning the larger problems of the Pacific sea floor. However, H. Niino has written extensively regarding the shallow seas around Japan, and R. Tayama and S. Hanzawa have published many papers on the islands of the northwestern Pacific Ocean.

This paper was prepared while the writer was a Fulbright Research Scholar in Japan during 1953. Through the courtesy of Dr. K. Suda, Chief of the Japanese Hydrographic Office, he was permitted access to the original sounding data on which the chart is based. This, of course, permits a much more critical analysis of the bathymetry than can be obtained by a study of the contoured chart alone because in drawing a contour map there are an infinite number of solutions.

At the writer's request the Japanese Hydrographic Office published this revised and

Anglicized edition of 6901 at cost of materials for The Geological Society of America in the interest of promoting closer scientific co-operation between the U. S. and Japan. The writer is responsible for some of the Anglicizing and for a few contour changes in the present edition but nothing more. The compilation of the data and the preparation of the chart is based on the efforts of many persons at the Japanese Hydrographic Office over many years. S. Miyamoto, T. Okawa, and K. Sumita were in charge of the 1939 version, while T. Okawa and N. Furumoto were in charge of the 1951 Chart 6901.

Hess (1948) published a geological interpretation of the U. S. Hydrographic Office's Chart 5485, which displays the bathymetry of the Philippine Sea and adjacent waters and covers about one-third of the area of 6901. The reader is referred to this excellent paper for a treatment by modern concepts of many of the larger problems of the northwestern Pacific.

ACKNOWLEDGMENTS

The work for this paper was done at the Japanese Hydrographic Office where many facilities were provided. At this office, Kanji Suda, Chief, and A. Irahara were most helpful. Sherman K. Neuschel, Charles G. Johnson, George Viele, and Helen L. Foster of the Tokyo office of the U. S. Geological Survey supplied many valuable criticisms and suggestions. Many facilities of that office including its numerous translations of Japanese papers were made available. The writer discussed many of the problems with various Japanese geologists. Especially helpful were S. Hanzawa of Tohoku University, H. Niino of the Tokyo College of Fisheries, and H. Kuno, T. Sakamoto, and T. Kobayashi of Tokyo University. At the U. S. Navy Electronics Laboratory in San Diego, California, the writer's colleagues, H. W. Menard, E. L. Hamilton, R. F. Dill, and Geo. Shumway, read the manuscript and made valuable suggestions. To these persons and organizations the writer is most grateful.

CONSTRUCTION OF THE CHART

Excluding the shallow seas which are well sounded, Chart 6901 is based on about 100,000 deep-sea soundings, using a contour interval of 500 m (270 fathoms). About half the soundings are from Japanese sources and the remainder from foreign sources, mainly from the U. S. and Great Britain. Sounding data up to 1945 are included. The Japanese Hydrographic Office has obtained almost no new deep-sea soundings since the end of World War II. The great majority of soundings are sonic, but some wire soundings are included. All the soundings are entirely lines of spot soundings; echograms from graphically recording echo sounders of modern design have played no part in the construction of this chart. Echo sounders are customarily calibrated for a velocity of sound in water of 4800 feet per second which is almost always slightly less than the average velocity of sound along a vertical path in the deep sea. The chart was constructed using these uncorrected soundings because hydrographic charts are constructed primarily as an aid to navigation. Thus, a ship taking soundings can compare its observations directly with the chart. However, it should be borne in mind that the sea floor of the deep Pacific actually is somewhat deeper than shown on charts by as much as a few hundred meters. Table 1 gives an approximation by which the true bottom depth can be obtained. However, few of the soundings, such as the CHALLENGER depth, are corrected soundings.

Soundings are never uniformly dispersed over a bathymetric chart but rather are plentiful along shipping lanes and sparse elsewhere. Thus the bottom is known in detail along these lines of communication so that many features can be delineated. The contourer generally is reluctant to extrapolate between two widespread sounding lines, and he has a subjective tendency to draw contours either normal to or parallel to a line of soundings. Thus trends of highs and depressions develop along shipping lanes. These, of course, are fictitious insofar as having any structural significance. On Chart 6901 such fictitious trends can be noted extending from the Philippine Islands to Guam and toward Hawaii and on the great circle route directly to Hawaii. All trends which line up with shipping lanes should be regarded with suspicion.

The interesting method of contouring by using a combination of white and dark-blue lines on a blue background was developed by

Prof. K. Tanaka of Kyushu University. This permits positive and negative relief to be readily distinguished. The illusion is obtained that sunlight is falling from the northwest so that each feature has a sunlit and a shaded side. As with an aerial photo, the chart must be viewed with the shadow falling toward the observer or a reversal of relief may result. It is worth while noting that the illusion can be obtained in shades of gray—*i.e.*, with a white and black contour line on a gray background—so that a color plate is not a necessity. The method should find wide use in bathymetric presentation for it is, for most purposes, superior to showing depth by shades of blue or by hachuring depression contours. For example, attempting to use hachures for showing depressions on bathymetric maps is especially perplexing because if sea level is used as the datum plane nearly all contours become depression contours.

TABLE 1.—PERCENTAGE CORRECTION TO BE ADDED FOR CONVERTING ECHO-SOUNDER DEPTH TO TRUE DEPTH IN THE PACIFIC OCEAN

For echo sounders calibrated at 800 fms/sec (Heck, 1926).

Latitude	Fathoms								
	600	1200	1800	2400	3000	3600	4200	4800	5400
	Meters								
	1097	2194	3292	4389	5486	6584	7681	8778	9875
60° N.	0.0	0.5	1.1	1.9	2.5	3.2	3.9	4.5	5.1
55° N.	0.3	0.8	1.3	2.0	2.6	3.2	4.0	4.6	5.2
50°–40° N.	0.6	1.0	1.5	2.0	2.6	3.3	4.0	4.6	5.2
35° N.	1.3	1.4	1.7	2.2	2.8	3.4	4.1	4.8	5.3
30° N.–40° S.	2.0	1.7	2.0	2.5	3.0	3.6	4.2	4.9	5.4
45° S.	1.3	1.4	1.7	2.2	2.8	3.4	4.1	4.8	5.3
50° S.	0.6	1.0	1.5	2.0	2.6	3.3	4.0	4.6	5.2
55° S.	0.3	0.5	1.1	1.7	2.3	3.0	3.7	4.3	4.9
60° S.	0.0	0.1	0.7	1.5	2.1	2.7	3.5	4.1	4.7

The scientific usefulness of a bathymetric chart is considerably enhanced if the soundings are shown on which the contours are based. Even when the soundings are so numerous that it is impossible to place them on the chart, their location indicated by a small dot is helpful in interpreting the contours. However, this often is not practicable and was not done on Chart 6901. Figure 3 was therefore prepared; it shows the number of the soundings deeper than 200 m by 5-degree squares. Thus the deep seas near Japan and especially to the south are comparatively well sounded; the Philippine Sea, the great undersea ridges, and the atoll regions are moderately sounded; but, in contrast, soundings are sparse in the great basin north and east of Japan. The deep trenches are everywhere poorly sounded because only the most recent echo sounders have been able to obtain good echo returns from these great depths. The shallow seas are well sounded except for the Sea of Okhotsk, so the number of shallow soundings are not shown in Figure 3.

GENERAL DESCRIPTION

General

Inasmuch as the land is contoured in the same manner as the ocean floor on Chart 6901, a direct comparison of the topography can be made. Because of the small scale of the chart, only large topographic features show up. It is immediately apparent that the greatest topographic features of the earth's surface lie submerged. The largest subaerial escarpment in this region is the east side of Formosa, but this is not impressive when compared to the enormous escarpments beneath the sea. The large swells and ridges of the sea floor also are without counterpart on land. High mountains rise above New Guinea, Celebes, Luzon, central Japan, and Kamchatka. But, again, these are small when compared to the great seamounts which rise from the ocean bottom. At least 150 seamounts already are known to rise more than 2500 m above their surroundings, whereas only 35 such mountainous areas are present on the land. The more subdued topography of the land, of course, at least in part, reflects the strong leveling action of running water. The greater irregularity of the land contours also results from stream erosion as well as from detailed contouring. Erosion, which plays an all-important role in the creation of sharp relief and the ultimate destruction of elevation on land, operates on a greatly reduced scale on the ocean floor.

The zero contour line or shore line is, of course, best known and is delineated in greatest detail. Especially in the East China Sea and in the Okhotsk Sea a great expanse lies between the shore line and 500-m isobath which closely marks the edge of the continental block. The continental shelf, although the best-surveyed submerged area, clearly stands out as the most featureless region on the chart. The known levelness of shelves mav be one reason for the widespread but obviously false belief that the ocean basins are also monotonously flat.

The largest-scale topographic features of the sea floor are the basins and the swells or rises. The swells are gentle, broad, and elongate elevations of the crust 200–300 miles across and many hundreds of miles long. Such swells should not be confused with ridges which are narrow and abrupt elevations. The axes of the major swells are shown on Figure 5. Features of this great size must be in isostatic balance, and their relief probably reflects differences of density of the earth's crust. The orientation of the major swells appears to be generally east-west. Seamounts appear to be concentrated on the swells although none have been discovered on certain of them. Thus, it may be more accurate to say that the seamounts are absent from the basins.

The northwest Pacific contains two basins of the unusually great depth of about 6000 m (Fig. 4). One of these can be termed the Northwest Pacific Basin, using this term in a restricted sense. It occupies the entire east-central portion of the chart and is the deepest of all ocean basins. The other lies beneath the western half of the Philippine Sea and can be termed the West Philippine Sea Basin. There are no other large regions of comparable depth anywhere.

Examination of sounding lines permits a determination of the roughness of the bottom such as cannot be gleaned from the chart. The Philippine Sea Basin, for example, shows a continuous series of ups and downs indicating a bottom that is rough in detail. In contrast, the basins between the groups of seamounts are characterized by smooth bottom suggesting a depositional plain. The basin enclosed by the semicircular Magellan Seamounts is especially noteworthy for its smoothness. However, the smoothness of the deep-sea basin is not comparable to that found in the intracontinental basin such as the Okhotsk Sea Basin and the Bering Sea Basin. The Bering Sea Basin is remarkably flat over at least its southern portion at 3720 m.

Deep-Sea Sediments

Many exploring vessels such as the TUSCARORA, CHALLENGER, NERO, ALBATROSS, and CARNEGIE have collected bottom samples from the northwestern Pacific Ocean. The most extensive collections, however, were made by the Japanese ship, MANSHU, which collected about 700 bottom samples. These have been charted and briefly described by Hanzawa (1928). Deep-sea deposits can be classified into hemipelagic, which have a large percentage of land-derived sediments, and pelagic sediments, which are composed of the remains of pelagic organisms, chemical precipitates, and products of deep-sea weathering. The former include blue muds and sands, volcanic muds and sands, and calcareous muds and sands; the latter include the inorganic deep-sea sediments known as red clay and the organic oozes such as globigerina ooze, radiolarian ooze, diatom ooze, and pteropod ooze. All these sediment types are present in the northwestern Pacific (Fig. 6).

Blue mud, composed largely of blue, gray, or green terrestrial detritus with an admixture of some pelagic material, fringes the land areas. It is generally found down to a depth of 4000 m, coating the continental slopes and extending out for some distance on the deep-sea floor where it gradually passes into red clay. Also, this sediment type is found in all the shelf-locked basins such as the Japan Sea Basin.

Volcanic muds and sands, composed largely of lapilli, pumice, and volcanic glass, are extensively developed on the submarine ridges which bear volcanic islands such as the Mariana Ridge, the Ryukyu Ridge, the Kuril Ridge, and the Aleutian Ridge, and also in many areas along the Philippines and the East Indies. Volcanic sediments are also commonly recorded in many of the trenches.

Calcareous muds and sands, composed of the broken remains of calcareous algae, corals, mollusks, etc., cover the flanks of the coral atolls and are also found along warm-water coasts where the deposition of inorganic detritus is slow.

By far the most widespread pelagic deposit is red clay; it covers most of the area of Chart 6901 in depths greater than about 4000 m. It shows a gradual transition into blue mud toward the land masses and into globigerina ooze toward the tropics and toward the large rises of the deep-sea floor. As well as being the dominant sediment in the Pacific Basin proper, it covers most of the floor of the Philippine Sea Basin.

Globigerina ooze, composed dominantly of the tests of pelagic Foraminifera, covers large tracts in the tropical and subtropical regions. The most extensive deposits are developed on the rises of the sea floor on which the Caroline and the Marshall Islands are developed. Typically the low-latitude regions at depths less than about 4300 m and the higher levels of the sea floor such as the tops of seamounts are covered with globigerina ooze.

Radiolarian ooze, a sediment composed of more than 20 per cent remains of the siliceous parts of radiolarians, appears to be present only in the trench off Guam. The world's greatest belt of radiolarian ooze is found in the eastern Pacific beneath the Equatorial Counter Current where its flow is intense; however, no radiolarian ooze is reported by Hanzawa (1928) from beneath the Counter Current in the western Pacific.

Pteropod ooze, composed largely of the calcareous shells of pelagic mollusks, is rare in the northwestern Pacific. It is reported by Hanzawa (1928) from only one locality in the Ryukyu region at 24°25′N. and 123°03′E.

Diatom ooze, composed of the siliceous frustules of robust types of diatoms and typically a high-latitude sediment, is reported from a few samples north of 41°, but red clay appears to be the more common sediment type. However, bottom samples are sparse north of about 35° so that it is as yet unknown if a broad band of diatom ooze spreads across the north Pacific as it does in high southern latitudes. Hanzawa (1935) has reported *Ethmodiscus* diatom ooze from 3 low-latitude localities in the western Pacific. This unusual sediment type, unknown elsewhere in the world, differs from high-latitude diatom ooze in that the latter is composed dominantly of the frustules of *Coscinodiscus*. Menard (1953) has recently shown that glacial marine sediments are widely distributed in the Gulf of Alaska, but there is no evidence of their presence in the northernmost western Pacific.

Faults on the Sea Floor

Many of the sounding lines with closely spaced soundings were plotted and studied for topographic features which might reveal crustal structure. For example, some sounding lines show an abrupt rise, marking a persistent new level of the sea floor. Such an escarpment may mark a major fault zone. Interpreting structure from topography has serious limitations, but, in the absence of stream erosion, the topographic expression of sea-floor structures can be expected to persist. As evidence of this, echograms may reveal "text book" examples of tilted fault-block mountains. An attempt must always be made to avoid accepting features which may be "artifacts"—*i.e.*, the result of human or instrumental errors.

The possible faults identified are plotted on Figure 5. They are shown by a straight line when the strike can be determined or by a circle with a cross in the center when the fault is revealed on only a single sounding line so that the strike is unknown. The faults shown generally are based on a steplike rise in the sea floor. Some are revealed by troughs which appear to be grabens. Such fracture zones are shown by a line with two arrows pointing inward. Many of the faults have a generally east-west strike. A discussion of the nature of the faulting is beyond the scope of this paper and, of course, would be highly speculative as the data are few. There are, undoubtedly, numerous faults on the sea floor which new surveys with modern echo sounders would reveal.

Of special interest is the discovery of a trough near 12°N. and 139°E. which may be a continuation of the Yap Trench into the East Philippine Sea Basin. Also, two deep en echelon troughs are present south of the central portion of the Caroline Swell, the deeper of which contains a sounding of almost 7000 m. Another trough, in the central part of the West Philippine Sea Basin, has a northwest-southeast strike. Hess (1948, p. 426–428) suggested that this structure may be a part of a master rift zone extending entirely across the Philippine Sea, but the Japanese soundings reveal no other faults along the strike of this feature. Another cleft in the bottom was found near 33°N. and 160°E. on the flank of swell in the center of the Northwest Pacific Basin (Fig. 2, Profile 1).

ARCUATE STRUCTURES

General

The trenches and their associated island arcs are the dominant features of Chart 6901. The arcs can be divided into two groups, the continental arcs of Kamchatka-Kuril Is.–Hokkaido, Japan, Ryukyu Is., and the Philippines, and the oceanic arcs, extending south from Japan and separating the Pacific Basin proper from the Philippine Sea.

Gutenberg and Richter (1949, p. 28–29) state that the following sequence of structures and attendant phenomena are typical of Pacific arcuate structures: (1) a trench or foredeep, (2) shallow earthquakes and negative gravity anomalies in a narrow belt on the concave side of the trough; generally, the ocean bottom rises here to a ridge with emergent small nonvolcanic islands, (3) maximum positive gravity anomalies and earthquakes at a depth near 60 km, (4) the principal structural arc (Late Cretaceous or Tertiary), with active or recently extinct volcanoes with quakes at depths of about 100 km, (5) a second structural arc with older volcanism, and (6) a belt of shocks at depths of 300–700 km.

It is now widely believed that the fundamental structure of arcs is the tectogene or a downbuckle of the earth's crust into subcrustal material. Kuenen (1936) and Griggs (1939) have shown by model experiments that less energy is required to fold the earth's crust inward than outward. Geanticlinal ridges appear to form on the active or concave side of the downbuckle which develops directly beneath or slightly on the concave side of the trench. The trench will remain as long as the crust is under horizontal stress but rises isostatically into an alpine mountain range if the stress is relieved. Presumably a downbuckle of suboceanic crust will have less buoyancy than one of continental material, owing to the absence of a sial layer, so there may be less tendency for the formation of alpine mountains in ocean basins.

Trenches

The great circum-Pacific belt of trenches reaches its maximum development in the region covered by Chart 6901. The deepest places in the world are found in this region including the CHALLENGER depth (10,863 m) near Guam, the CAPE JOHNSON depth (10,479 m) in the Philippine Trench, and the RAMAPO depth (10,680 m) in the Japan Trench. Obtaining accurate sounding in these great depths is difficult so that the presently determined depths may not stand the test of later critical surveys.[1] The trenches are still poorly sounded because only the most modern echo sounders can record the greatest depths; ships over the deeps are almost invariably "off soundings". But it is almost certain that if deeper spots are found anywhere in the world they will be discovered in this region. Also, the trenches probably have a simpler form than shown on Chart 6901. Some of the sills shown between the deep spots in the trenches and some of the irregularity, especially of the Mariana Trench where soundings are conflicting, undoubtedly will be eliminated by future surveys.

Only the western end of the Aleutian Trench appears on Chart 6901 where it intersects the Kamchatka Ridge. However, the soundings do not preclude the possibility that the Aleutian Trench continues on to meet the Kamchatka Trench. It certainly extends farther west than presently indicated because the 1953 Trans-Pacific Expedition of Scripps Institution of Oceanography discovered that it was still strongly developed at 53.5°N. and 168.0°E. with an axial depth of 3660 m.

A series of connected trenches is strung from Kamchatka to Palau, a distance of almost 4000 miles (throughout, reference is to nautical

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[1] As a case in point, three crossings of the Ramapo Deep were recently made with an Edo echo sounder by the SPENCER F. BAIRD of the Scripps Institution of Oceanography, but the greatest depth found was 4995 fms uncorrected which is 5250 fms or 9607 m corrected by Table 1. Thus considerable doubt is thrown on the validity of the USS RAMAPO's determination.

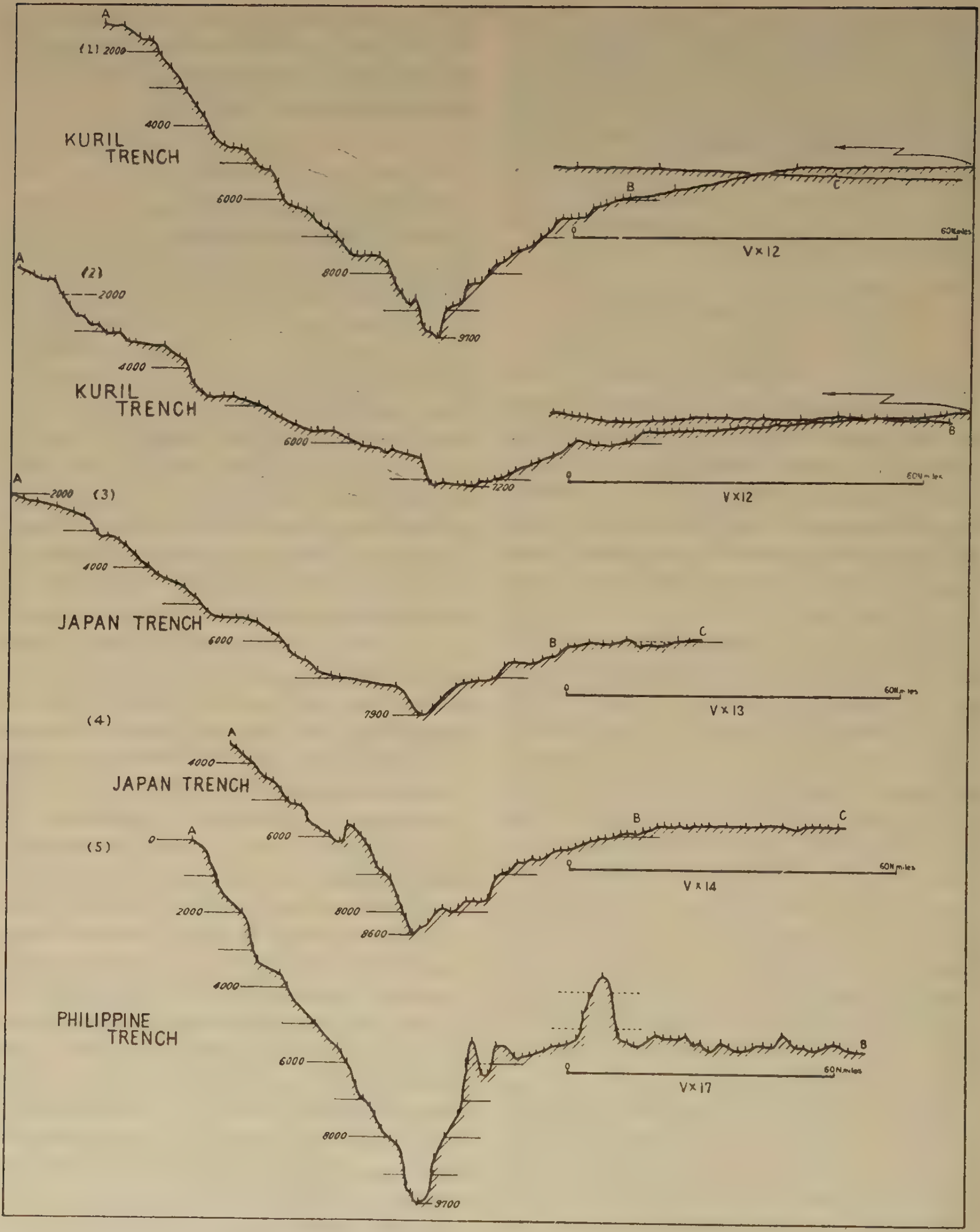

Figure 1.—Sounding Profiles across Trenches

miles). Although the trench is, in a general sense, continuous, it is broken into a series of arcuate segments which intersect one another at sharp angles. From north to south these trenches are the Kamchatka Trench, the Kuril Trench, the Japan Trench proper off Honshu, the Izu-Bonin Trench, the Mariana Trench, the Yap Trench, and the Palau Trench. On the west side of the Philippine Sea lies the great Philippine Trench and the weakly developed Ryukyu Trench. The Ryukyu Trench extends along southern Japan, but here the relief is only 500 m.

Five trench profiles are presented in Figure 1.

In cross section they are check-shaped, having a steep landward slope and a gentle seaward slope. The bottom of the trench is commonly narrow. As a case in point, the Danish oceanographic vessel, GALATHEA, had difficulty remaining over the axis of the Philippine Trench while attempting to dredge the bottom (A. Bruun, personal communication). Unpublished data of R. Fisher from the Trans-Pacific Expedition shows that the bottoms commonly are flat indicating considerable sedimentation.

In plan, the arcuate form of many trenches is well known—*e.g.*, the Aleutian Trench closely approximates the arc of a circle with a radius of curvature of 750 miles. The Mariana arc has a radius of curvature of 400 miles and almost completes a semicircle. This led Lake (1931, p. 150) to suggest that they represent the intersection of a low-angle thrust plane with the earth's spherical surface, but this idea has not been widely accepted. Hess (1948, p. 441) compares the form to that developed by plastic or pseudoviscous flow—that is, like the curving lines that traverse a glacier. The check-shaped profile with the deepest point immediately at the base of the steep landward slope is consistent with the idea that the landward side is being shoved out over the sea floor.

In connection with the weak development of the Ryukyu Trench, Hess (1948, p. 421–422) has made the interesting suggestion that it belongs to an earlier period of deformation—being formed in the mid-Mesozoic whereas the others came into existence at the end of the Mesozoic. He suggests that it is a remnant of a once-extensive trench system which is now mainly above sea level—extending from Kamchatka, through the "backbone" of Hokkaido, across Honshu and Kyushu, thence along the present Ryukyu Trench into Taiwan, thence through Luzon and Palawan in the Philippines (Fig. 5). As evidence he cites a chain of peridotite intrusions which he believes are intruded only into tectogenes and only shortly after the initial buckling.

The seismicity associated with the trenches of the western Pacific is extremely strong and is part of the great circum-Pacific seismic belt. The zone extending from central Honshu to Kamchatka is the world's most seismically active region. A major bifurcation in the circum-Pacific belt occurs in central Honshu with major activity extending down the Honshu-Mariana-Palau Ridge and lesser activity extending along southern Japan and the Ryukyu Arc. Almost all activity is associated with the arcuate structures. The Pacific Basin proper is a region of seismic calm although some strong shallow shocks are found near the western part of the Caroline Swell. Large tsunami or seismic sea waves commonly result from earthquakes along the trenches, suggesting abrupt changes of earth level of much greater magnitude than are observed on the land.

A not previously recognized aspect of trenches is the presence of a broad low swell on the oceanic side of many of them. Such a swell is developed from Japan to Kamchatka and also on the outside of the southern part of the Philippine Trench. The nature of the swell can be seen in the west portion of Profiles 1 and 2 of Figure 1. This type of swell was first noticed by the writer in connection with the trench off Baja California.

Trenches invariably cut across other structures and are not themselves interrupted, indicating their great structural importance and/or that they are young structures. A striking aspect of the arcuate structures south of Japan is that they abruptly cut off the seamount groups. This is especially marked in the case of the Caroline Group because it is transected where it has maximum development.

Honshu-Mariana Ridges

Two great ridges rise behind the trenches extending south of Japan. These can be termed the First Honshu-Mariana Ridge, extending from the Izu Islands through the Volcano Islands to the Mariana Islands and to a little south of Guam, and the Second Honshu-Mariana Ridge, extending from Honshu to the intersection of the Mariana and Yap trenches and lying symmetrical to, but from 100 to 150 miles west of, the First Ridge. These ridges have the form of an inverted sickle. In the East Philippine Sea Basin, the sea floor rises with a gently upward sweep over a distance of 150 miles toward the second ridge. These ridges are clearly geanticlines and presumably are crustal waves related to the tectogene. Apparently the earth's crust was deformed into two waves in front of the primary synclinal wave which collapsed into a downbuckle.

Another geanticlinal ridge, on which the Bonin Islands are developed, lies east of the northern wing of the First Honshu-Mariana Ridge. The Bonin Ridge lies close to the trench and seems to cause a displacement of the trench to the east inasmuch as it lies close to the strike of the Izu Islands portion of the Japan Trench.

The First Honshu-Mariana Ridge is more strongly developed than the second. They are slightly asymmetric, with the east slope commonly steeper than the west. The Second Ridge nowhere pierces the surface, but there are five shoal banks in the Mariana region which mark former islands now truncated by wave action. Many volcanoes are superposed on the First Ridge, and along it there is volcanic activity in the Izu Islands, in the Iwo Islands, and in the Marianas. The volcanic axis appears to lie slightly west of the structural axis, at least in the southern Marianas. Some of the seamounts resting on the Second Ridge are probably of volcanic origin, but this is not proven because there is no active volcanism.

A search of the soundings revealed no evidence of guyots (*i.e.*, excluding banks, and defining guyots as flat-topped seamounts deeper than 300 meters, thus indicating subsidence rather than merely truncation during a Pleistocene lowering of sea level). Thus, these ridges probably always have been positive elements with a persistent tendency to rise.

A search was made for the presence of a third ridge lying in the East Philippine Sea Basin and symmetrical to the other ridges but of less relief. No such ridge was discovered. The Kyushu-Palau Ridge might be considered as the third ridge, but it probably has had a separate history from the Honshu-Mariana ridges. It is discussed later.

SEAMOUNT GROUPS OF THE PACIFIC BASIN

General

The most striking aspect of the chart is the extensive groups of seamounts, some of which pierce the surface but others of which are deeply submerged. Many of the seamounts are truly enormous as can be realized by comparing them to the highest mountain in Japan, Mt. Fuji, located 1° west of Tokyo Bay. The seamounts rising from the deep-sea floor are much larger than those which are superposed on the geanticlinal ridges and also much larger than volcanic mountains on land. This is partly due to coral reefs capping some of the seamounts but also to the absence of erosion and probably to mountain building on a greater scale than is known on land. The hydrostatic support of the water lessens the weight of the rock on the sea floor by a little more than one-third. Also a shorter magma column may be present because of the possible closer position of the sea floor to a possible world-encircling magma layer. These may be contributing factors to the large growth of submarine volcanoes.

There is almost no information on the rocks composing the seamounts. However, on the Scripps-Navy Mid-Pacific Expedition, olivine basalt was dredged from Sylvania Seamount near Bikini and from the slopes of Bikini atoll. Where the foundation rocks of the seamount are exposed above the ocean surface, as at Truk, Ponape, and Kusaie, it consists of basic volcanics. Judging from their circular plan and steep flanks, most of the seamounts are extinct volcanoes. This is probably true even though the circular form of many of the seamounts is not firmly established but rather is a result of generalized contouring of few data. Menard (in press) by surveys and dredge hauls shows the volcanic nature of similar seamounts in the northeastern Pacific. The seamounts are probably composed of volcanic rock of great uniformity and olivine or nepheline basalt are probably the dominant types.

The seamounts are not randomly disposed but, rather, are arranged in broad belts. The linear arrangement is not nearly so perfect as that which characterizes the volcanoes associated with the arcuate structures; thus, a different type of volcanism is indicated. Seamounts in the Pacific Basin usually seem to be developed on broad linear rises or swells of the crust. For this reason Dietz and Menard (1953, p. 110–112) suggested that the swells and the seamounts are genetically related. Possibly the swells develop over thermal convection currents in the earth's mantle. Tension cracks may then develop in the swell along which magma finds access to the surface. Little is known concerning the mechanism of deep-sea volcanism so that this is a fertile field for future research. The mechanism of growth certainly appears to be different in many ways from that observed in the subaerial environment.

No deep-sea volcanic activity is known in the region of the chart, and in fact deep-sea volcanism is rarely reported anywhere in the world, probably because its detection is difficult. Shallow submarine volcanism is known in several places along the First Honshu-Mariana Ridge. An active sulfur boil is known about 50 miles west of Tinian. A second and presently active boil exists west of South Iwo Jima. An island once appeared at this spot but later disappeared. The most spectacular submarine volcanism is the activity about 200 miles south of Tokyo at Myojin Reef which has been intermittently active for at least 50 years. Most recent activity began in September 1952 and continues. As of the present writing (February 1954) an island has been formed three times only to be later destroyed. Over 100 explosions at this volcano were detected in September 1952 along the California coast more than 8000 km distant by underwater listening (Dietz and Sheehy, 1954).

Emperor Seamounts

A great linear range of seamounts dominates the northeastern portion of Chart 6901 and extends from the vicinity of the intersection of the Aleutian Trench with the Kamchatka Trench to the vicinity of 30°N. and 174°E., a distance of about 1500 miles. This entirely submerged range cannot be identified in terms of well-known geographic landmarks as, for example, in the case of the Kyushu-Palau Ridge, so that a nongeographic name is appropriate. Hence, they are provisionally termed the Emperor Seamounts, and the names of ancient Japanese emperors are applied to several of the most prominent. Soundings in this region are sparse so that the seamounts are based on few data. Future surveys will undoubtedly produce important modifications in the bathymetry shown, and new seamounts will almost certainly be added to the chain. But the present soundings are sufficient to establish the chain as a genetically related group of unusually large seamounts. The north-south trend of the seamounts is noteworthy inasmuch as northeast-southwest is the usual trend of Pacific Island chains, while an east-west trend is common for submerged structures. The southern end of the chain ties into the western end of the Hawaiian Swell with its many superimposed seamounts (Dietz and Menard, 1953, Fig. 1).

TABLE 2.—DATA ON EMPEROR SEAMOUNTS* FROM CHART 6901 SOUNDINGS

Numerical Name	Name	Least Depth (meters)	Total Relief (meters)	Depth of Flat Top (meters)
52–170	—	2976	1900	3000
51–168	—	2352	2700	—
49–169	Tenchi	1857	4300	—
46–169	Jimmu	1299	5100	1340
45–170	Suiko	1572	5000	1600
41–170	Nintoku	949	4200	960
38–171	Jingo	2194	—	—
38–170	Ojin	1848	4600	—
34–172	Kinmei	1560	4500	—
33–172	Yuryaku	300	5000	—
32–173	Kanmu	292	5200	300
30–174	—	1969	3200	—

* The 1953 Trans-Pacific Expedition of the Scripps Institution of Oceanography provided important new data on the Emperor Seamounts, but these are not incorporated into the table inasmuch as it shows Chart 6901 data. Jimmu has least depth of 1281 m (uncorrected). It is definitely a guyot with a break-in-slope at 1500 meters and a gently shoaling depth up to its top. Suiko is a large and complicated feature 60 miles across its top and has several flattened summits. The shoalest summit has a least depth of 1090 m (uncorrected). It also is definitely a guyot with break-in-slope at 1280 m followed by gently shoaling bottom up to the minimum depth. A new guyot with a depth of 1895 m was discovered south of Suiko at 43°-07′ N. and 170°-20′ E. At the north base of Jimmu from 2800 fathoms, an assemblage of volcanic gravel was dredged including angular to well-rounded pieces. The pumice may have been rafted, but the rounded gravel most likely was rounded at the top of the seamount, when it was an island, and later moved down the flank. Examination by H. Kuno shows one rounded rock to be tuffaceous shale, an angular piece to be augite-bearing hypersthene andesite, and the pumice to be hypersthene dacite pumice. This suggests that Jimmu may not be composed of volcanics of the normal intra-Pacific type.

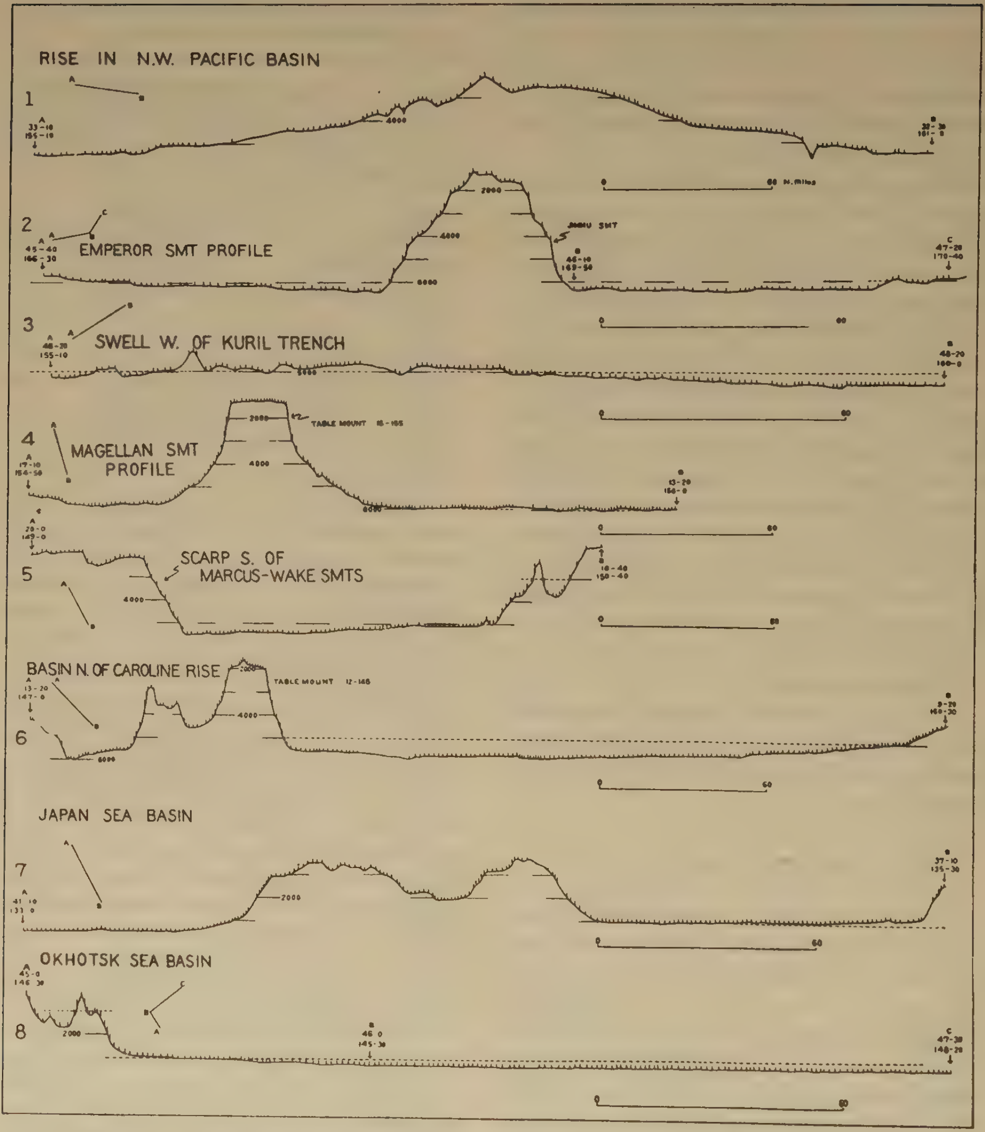

Figure 2.—Some Representative Sounding Profiles in the Northwest Pacific

At its northern end, the Emperor Seamounts connect with an extensive region of high relief termed the Komandorski Ridge. The region is sparsely sounded so that the nature of the elevated region is uncertain. The western side appears to be bounded by an abrupt and straight escarpement of 2000 m relief. On one sounding line approaching this escarpment, steplike rises of the sea floor suggest faulting.

The enormous size and relief of many of the Emperor Seamounts is striking (Table 2). Four of them have a relief of 5000 m or more, placing them among the earth's great mountains. All the seamounts are deeply submerged except Yuryaku and Kanmu at the southern end of the chain, both of which have a summit depth of about 300 meters. However, additional soundings undoubtedly will reveal many shoaler spots than are now known. Japanese fishermen sometimes find a fish known in Japan as "menuki" in the stomachs of tuna in this region. (H. Niino, personal communication) Menuki are bottom fish which near Japan are found at a maximum depth of 500 to 1000 m. They suggested the presence of submarine highs before such were discovered. They also suggest the presence of more shoal areas than are now known.

Five of the seamounts of the Emperor Seamounts appear to have flat tops and thus are guyots (Hess, 1946, p. 772) or tablemounts.[2] In the case of the other seamounts of the chain data are insufficient to determine whether the summits are flat or peaked. Hess (1946, p. 788–790) considered guyots to be ancient islands truncated by wave action and subsequently drowned. More recent work has tended to confirm this belief (Carsola and Dietz, 1952, p. 493; Menard and Dietz, 1951, p. 1283; Hamilton, 1953, p. 204–206). The lack of concordance in the depth of the flat tops is striking. From the Chart 6901 data Kanmu has a flat-topped depth of 300 m; Nintoku's depth is 960 m; Jimmu's depth is 1340 m; and Suiko's depth is 1600 m; and the depth of Seamount 52–170[3] is 3000 m.

All the guyots are too deep to be explained by truncation during a low Pleistocene stand of sea level because most geologists agree that the greatest lowering during the Ice Age was less than 150 m. Thus guyots indicate local or regional subsidence or drowning by a rise of sea level. There are, of course, many possible ways in which the submergence of guyots may have taken place. Hess (1946, p. 789–790), for example, considered that they are extremely ancient (*i.e.*, formed prior to the advent of reef building corals or in the Precambrian) and that their submergence is related to a slow rise of sea level caused by sedimentation in the deep sea. Hobbs (1944, p. 223–224, 260–268) suggested subsidence of the Pacific Basin as a whole. On the other hand, the present writer is inclined to favor local isostatic subsidence of large seamounts because of the great load they place on the earth's crust. Depressed zones or "moats" have been found around the base of some guyots which tends to support the latter idea (Menard and Dietz, 1951; Dietz and Menard, 1953). Soundings suggest such a moat at the base of Jimmu (Fig. 2, Profile 2).

Marcus-Wake Seamount Group

An east-west 1200-mile long broad band of seamounts is present east of the trench system and between latitudes 17° and 21°N. Only two of these seamounts pierce the surface of the sea. The group can be conveniently termed the Marcus-Wake Seamount Group. This group appears to be an extension of the submerged Mid-Pacific Mountains described by Hamilton (Ph.D. thesis, Stanford University, 1952; 1953) which begins west of Hawaii and extends to about 170°E. Only the westernmost portion of the Mid-Pacific Mountains can be seen on Chart 6901 where they are delineated as a generalized area of high relief. Like the Mid-Pacific Mountains, the Marcus-Wake Group is developed on a low swell in the ocean floor.

The seamounts are deeply submerged, generally more than 1000 m. At least some of them display flat tops and, thus, are guyots. Seamount 20–160 has an especially well-developed flat top at 1450 m. Seamount 26–145 has a flat top at 1100 m which appears to be tilted to the southeast. Seamount 27–145 rises to within 80 m of the surface. It has been surveyed in detail and displays a sharp peak, suggesting that it may be a recently formed mountain.

Several sounding lines show that the southern margin of the Marcus-Wake Group is terminated by an abrupt east-west escarpment which may mark a major fracture zone in the Pacific Basin.

Magellan Seamounts

Immediately east of the Mariana Trench, between the Marcus-Wake Seamount Group and the Caroline Group, a group of seamounts forms a semicircle with a 200-mile radius and open to the south. The name Magellan Seamounts is provisionally applied to the group inasmuch as no good geographic name can be applied and the use of historical personages is in conformance with other names in the region—*e.g.*, Caroline, Marshall, and Gilbert. Magellan, of course, was the first explorer to cross these waters en route to his discovery of the Marianas. There are at least 14 major seamounts in this group, all of which are submerged to a depth of 1200 m or more. Soundings in this region are sufficiently dense so that additional surveys will not greatly alter the appearance of this group as now known. The seamounts embrace a broad, smooth, and featureless basin at 6000 m.

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[2] The term "tablemount" is used in preference to "guyot" on U. S. Navy Hydrographic Office charts and is quite descriptive. However, the term, "guyot" is now well established in the literature so that it is used in this paper.

[3] In this paper unnamed seamounts are identified by their geographic co-ordinates. Thus a seamount at 25°–10′ N. and 171°–10′ E. is termed Seamount 25–171. The location of such a seamount could be more closely defined by terming it Seamount NE 25.2–171.2, thus indicating earth's quadrant and fractions of degrees. But such nomenclature is cumbersome and unnecessary if the earth quadrant is apparent and the feature is large or sufficiently isolated to be uniquely identified by listing the nearest degree of latitude.

This group apparently belongs to the Pacific Basin proper and is not an offshoot of the Mariana Ridge inasmuch as the west limb of the group lies tangent to the Mariana Trench rather than transecting the trench and connecting onto the Mariana Ridge. The Magellan Seamounts are thus quite different, for example, from the hook-shaped Bowers Bank Ridge in the Bering Sea Basin which is an offshoot of the Aleutian Ridge. The semicircular form of this group is noteworthy inasmuch as structures in the Pacific Basin proper generally are straight.

The three seamounts making up the east limb of the crescent are probably guyots. From north to south, the flat-top depths are 1250 m, 1500 m, and 2000 m. The 5000-meter-high northernmost seamount of the three, *i.e.*, Seamount 16–155, has a remarkably flat top about 15 miles across (Profile 4 of Fig. 2).

Seamount 17–154 appears to have an irregular summit, but the three other seamounts at the top of the semicircle probably are guyots (16–152 flat at 1300 m, 17–153 flat at 1200 m, and 18–151 flat at 1800 m). The seamounts along the western limb are deeply submerged and are connected by a continuous ridge. Here they lie tangent to the Mariana Trench and possibly have been depressed by the formation of that foredeep. Seamount 12–148, at the base of the western limb, is a guyot with a flat top at 1800 m.

Marshall and Gilbert Seamount Group

The Marshall Islands form a broad band of seamounts extending from 5°N. to 15°N. and are near the eastern margin of the chart. The Gilbert Islands form a southern tail on the Marshalls. Here, as in the other groups, the seamounts have a strong "family" resemblance. Most of these seamounts reach the surface where they form coral atolls of low relief. Foundation rock is nowhere exposed, and only Quaternary coral-reef formations are present. Like most of the other island chains in the central Pacific, the Marshalls and Gilberts display a northeast-southwest trend. The marine geology of the Marshall Islands is described in considerable detail by Emery, Tracey, and Ladd (in press). They describe several guyots. Chart 6901 is based on few soundings in this region so that the bathymetry is poorly portrayed.

Age of the Pacific Basin Seamount Groups

As noted earlier the Pacific Basin seamount groups almost certainly are volcanic rather than orogenic mountains. On the continents the development of any particular volcanic mountain chain is confined to a short geological time span. It is reasonable to assume that this is also true for sea-floor volcanic chains. Thus, if the age of a single seamount can be determined, its age may roughly date the entire group.

Beginning with the Mid-Pacific Mountains (whose western end only is shown on Pl. 1) a well-integrated mid-Cretaceous (Aptian to Cenomanian) reef coral-rudistid fauna has been dredged from two guyots (Hamilton, Ph.D. thesis, Stanford University, 1952; 1953, p. 204–205). Fossil pelagic Foraminifera of late Paleocene and early Eocene age have also been recovered from the summits of three of these mountains. Olivine basalt was dredged along with the reef fauna so that the fossil reefs apparently were in immediate contact with the volcanic foundation rock. Thus, these particular volcanoes, and probably the Mid-Pacific Mountains in general, are pre-Aptian to Cenomanian. The fact that faunas of the same age were recovered from two widely separated tablemounts strongly supports the concept of synchronous volcanism. It appears likely that the seamounts pierced the surface of the ocean, were truncated by wave action, and then were covered by a spot growth of reef coral, all in mid-Cretaceous time. However, of course, the foundation rock cannot

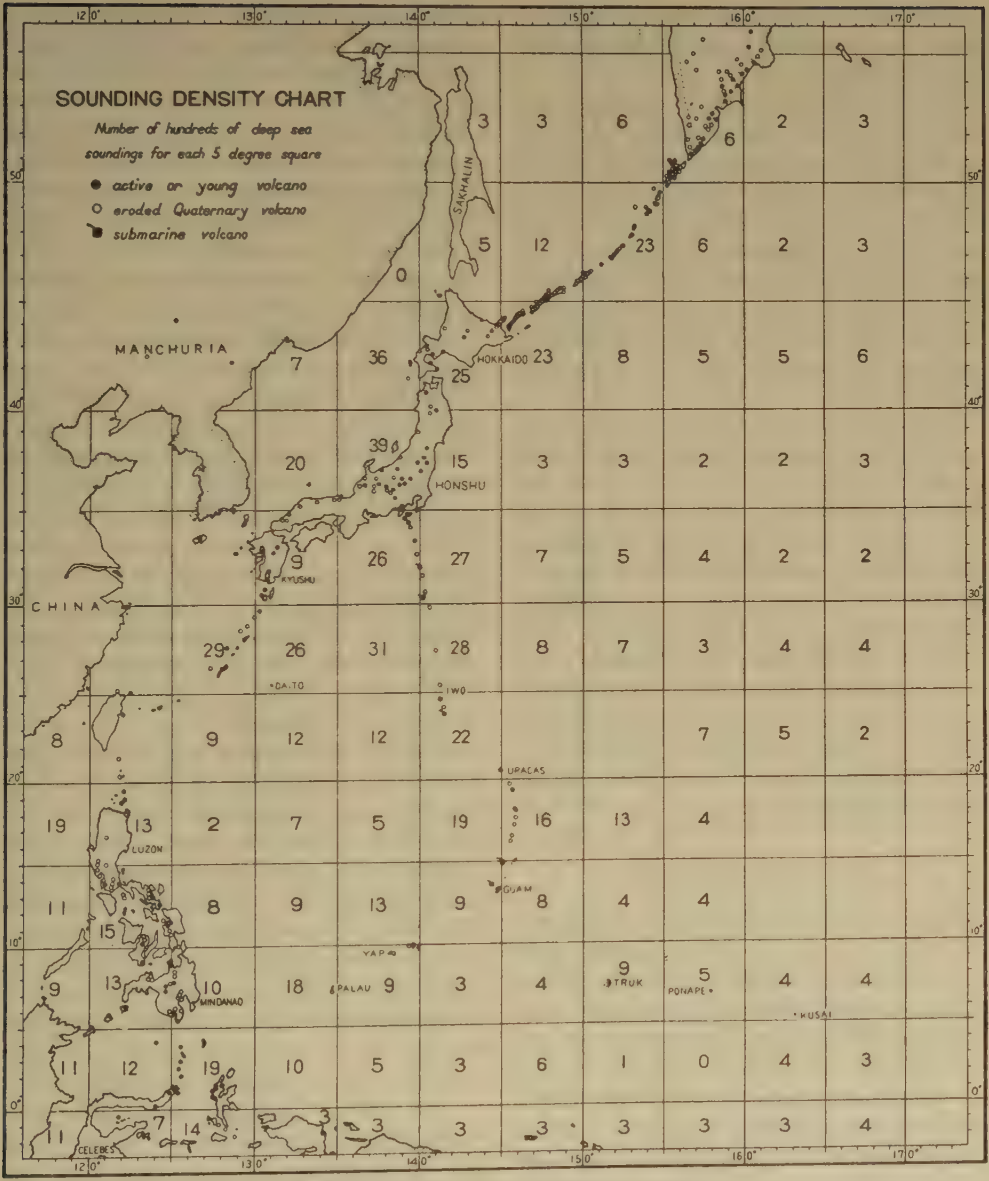
SOUNDING DENSITY CHART
Number of hundreds of deep sea soundings for each 5 degree square
● active or young volcano
○ eroded Quaternary volcano
submarine volcano
120°
130°
140°
150°
160°
170°
50°
40°
30°
20°
10°
0°
SAKHALIN
MANCHURIA
HOKKAIDO
HONSHU
KYUSHU
CHINA
DA.TO
IWO
URACAS
LUZON
GUAM
YAP
PALAU
TRUK
PONAPE
KUSAI
MINDANAO
CELEBES
3 3 6 6 2 3
0 5 12 23 6 2 3
7 36 23 25 8 5 5 6
20 39 15 3 3 2 2 3
9 26 27 7 5 4 2 2
29 26 31 28 8 7 3 4 4
8 9 12 12 22 7 5 2
19 13 2 7 5 19 16 13 4
11 8 9 13 9 8 4 4
15
9 13 10 18 9 3 4 9 5 4 4
11 12 19 10 5 3 6 1 0 4 3
11 7 14 3 3 3 3 3 3 4

FIGURE 3.—SOUNDING DENSITY CHART

be definitely dated by the overlying reef limestone.

The Marcus-Wake Seamount Group appears to be a western extension of the Mid-Pacific Mountains. Many guyots of the two groups are deeply drowned to a similar depth of about 1800 meters. Hence the Marcus-Wake Group may be of the same age as the Mid-Pacific Mountains. Future dredging on the tops of the guyots or drilling of a well to the foundation rock on Marcus Island or Wake Island is needed for proof.

The Marshall Islands and the Gilbert Islands are mostly composed of atolls although some guyots are also known, and the two groups probably have a similar history. Recent drilling on Eniwetok Atoll has revealed Eocene in contact with the olivine basalt foundation at 4154

(Ladd *et al.*, 1953). This suggests an early Tertiary age for the volcanoes of the Marshall and Gilbert Islands.

The Caroline Islands appear to be the youngest of the seamount groups. Deeply submerged guyots are not known to be associated with the group. Volcanic islands still persist at Truk, Ponape, and Kusaie. These islands are deeply eroded and weathered. Miocene fossils have not been found, so S. Hanzawa (oral communication) considers them to have been produced by Pliocene volcanism. Thus, one may tentatively assign a late Tertiary age to the Caroline Islands.

There are few data on which to venture a guess regarding the age of the Emperor Seamounts. However, Seamount 52–170, in the axis of the Aleutian Trench, may be the northernmost member of this chain. Although there are only a few soundings, they suggest a flat top so that this seamount is probably a guyot with an unusually great platform depth of 3000 m. The unusually deep drowning of this guyot may be accounted for by the formation of the Aleutian Trench which probably originated in the late Cretaceous (Hess, 1948, p. 421). The guyot must have been in existence prior to the formation of the trench.

Philippine Sea Basin

The nearly 400,000 square miles of Philippine Sea Basin is bounded on the west by the southern half of Japan, the Ryukyu Island, and the Philippines and on the east by the arcuate seafloor ridge from Japan to the Palau Islands. This abyssally deep basin is cut into an east and west basin by the Kyushu-Palau Ridge. The east basin is somewhat shoaler, and it rises gently toward the Honshu-Mariana Ridge. The west basin is unusually deep, and, although regionally level, sounding lines show that it is rough in detail, suggesting the absence of a thick sedimentary blanket.

The Philippine Sea Basin differs from the Pacific Basin proper in the absence of very large seamounts. However, a region of rugged topography which can be termed the Daito Mountains lies at the north end of the West Philippine Sea Basin, nested between the Ryukyu Trench and the Kyushu-Palau Ridge. The mountainous area is largely submerged, but two peaks pierce the surface, one to form N. and S. Daito Island and the other to form Oki ("Outside") Daito Island[4]. A well drilled on N. Daito Island in 1934–1936 to a depth of 432 m encountered shallow-water coral-reef limestones not older than late Oligocene, but the foundation rock was not reached by the drill (Hanzawa, 1940). Cole (Ladd *et al.*, 1953, p. 2277), who also has studied these cores, places the bottom as lower Miocene. Thus, considerable subsidence and a mid-Tertiary or older age is suggested for the Daito Mountains.

The Daito Mountains are well sounded for a deep-sea region, but the soundings are not accurately positioned; thus many of the soundings are conflicting. Nevertheless, it is clear that the topography is complex and different from that of the mountain groups in the Pacific Basin proper. Large northeast-southwest ridges dominate the structure of the Daito Mountains and suggest that, in contrast to the Pacific Basin seamount groups, this is an example of an orogenic mountain range where volcanism has played only a minor role.

In geological literature (*e.g.*, Stearns, 1945) the belief is sometimes expressed that the Andesite Line which is generally drawn along the trench axes of the seawardmost trenches marks the true boundary of Asia and that the region inside this line was formerly a continent. On Chart 6901 the area thus considered by some persons as continental is essentially that occupied by the Philippine Sea Basin plus the Honshu to Palau ridges. Gutenberg and Richter (1949, p. 26, 57–58) state that a "continental structure" is indicated for the Philippine Sea by the velocity of shallow earthquake waves which cross it. These writers apparently mean that a crustal layer of intermediate or "sialsima" composition overlies the sima ("ultrasima" of some writers). They do not imply the former existence of a continent in this region but only that it is non-Pacific Basin from a crustal-structure point of view.

Bathymetrically, a sialsima layer extending over a large region should be indicated by shoaler bottom. The Philippine Sea Basin east of the Kyushu-Palau Ridge generally is about 500 meters shoaler than the deep Pacific, suggesting the presence of a thin low-density crustal layer or of sedimentary fill, but the region west of that ridge is one of the deepest expanses of ocean floor in the world. Large irregular blocks of high relief such as those present in the Japan Sea Basin, which might be interpreted as sialic remnants of a continent, are absent from the Philippine Sea Basin.

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[4] Chart 6901 is in error in the labeling of S. Daito Island which should read Oki or "Outside" Daito Island.

There are no reports of granitic outcrops or granitic xenoliths, which would suggest a sialic foundation, in the lavas of the islands along the eastern margin of the Philippine Sea. The andesites on these islands are considered by Kuno (oral communication, 1952) to be of the "pigeonitic rock series" and thus to have been produced by fractional crystallization from a basaltic magma rather than by sialic contamination which produces a "hypersthenic rock series" according to this writer. The crystalline schist on Yap is sometimes referred to as "continental rock", but there is no compelling evidence to show that it is not a metamorphosed oceanic sediment. All in all, the argument for the existence of a former continental mass in the region of the Philippine Sea is not convincing. However, the forces that have buckled Asia and fragmented the continental margin have extended out to sea to form the oceanic ridges extending from Honshu to Palau. This is ample reason for considering the Andesite Line as marking the limit of the Pacific Basin proper from a structural point of view even if not in terms of crustal composition.

Islands

General

The islands of the northwestern Pacific can be classified as (1) marginal continental islands, (2) islands on the submarine geanticlinal ridges, and (3) islands rising from the abyssal sea floor. The continental islands are those lying inside of the continental slope from Kamchatka to Japan and thence to Formosa, the Philippines, and New Guinea. Many of them are large and geologically complex. Their geology is related to that of Asia rather than to the Pacific Basin, so no discussion of them is necessary here.

Except for Parece Vela Reef on the Kyushu-Palau Ridge and the volcanic Bonin Island on the Bonin Ridge, all the geanticlinal islands are confined to the First Honshu-Mariana Ridge. The Second Honshu-Mariana Ridge is devoid of islands although several shallow banks are known. The island groups surmounting the first Honshu-Mariana Ridge, from north to south, are the Izu Islands. the Volcano Islands, the Mariana Islands, the Yap Islands, and the Palau Islands.

The seven islands of the Izu Islands are volcanic, and several of them are active. South of the Izu Islands lie the Volcano Islands or North, Middle, and South Iwo Jima. A submarine volcano is presently active near South Iwo Jima. The northern Marianas are volcanic islands of andesitic composition. Uracus is presently active, but others are extinct. The southern Marianas or Saipan, Tinian, Aquijan, Medinilla, Rota, and Guam are composed of Tertiary limestone, and all show terrace topography. These limestones are elevated coral reefs or the upper Eocene and upper Oligocene which, in turn, are partly covered by upper Pliocene or Pleistocene limestones. Beneath the upper Eocene rocks are tuffs and agglomerates of andesites and liparites, suggesting the introduction of volcanism in the Eocene. The southern Marianas mark the emergent crest of the geanticlinal ridge. The volcanic axis of this ridge lies to the west, and two submarine volcanoes are known.

Yap is underlain by crystalline schists of unknown age. Volcanic agglomerate covering the schist contains Tertiary fossils so that the schist is Tertiary or older. The main island of the Palau Islands is composed of andesitic agglomerate containing Eocene Foraminifera and indicating Eocene volcanism. The Bonin Islands, apparently lying on a geanticlinal ridge frontal to the First Honshu-Mariana Ridge, also have volcanic rocks of Eocene age.

The islands rising from the deep-sea floor are geologically simple. Truk, Ponape, and Kusaie in the Carolines are all composed of basaltic rock. All the other Caroline Islands, the Marshalls and Gilberts, Marcus and Wake, and the Daito Islands in the Philippine Sea are Quaternary coral reefs. Inasmuch as the volcanic islands of the Carolines all lie toward the eastern end of the group, volcanism probably has progressed from west to east. Such a probable eastward progression of volcanism is noteworthy because it is found in the Hawaiian Islands, the Society Islands, and the Revillagigedo Islands.

The above data on the islands have been mainly extracted from Hanzawa (1941) and Tayama (1952). Tayama's chart of the islands is presented as Plate 2 inasmuch as it summarizes many facts about the Northwest Pacific oceanic islands. It also demonstrates the strong family resemblance of the islands belonging to any particular group.

Raised Islands

It is common knowledge that many of the islands superposed on the First Honshu-Mariana Ridge show evidence of having been elevated (Pl. 2). This is particularly marked in the southern Mariana Islands. Bridge (1948, p. 222) has summarized the situation as follows:

> "In the southern Mariana Islands the Tertiary and early Quaternary limestones have been raised as much as 1,500 feet above the present sea level (Rota). Locally the strata have been highly tilted and the surfaces of marine terraces have been offset and tilted by faulting (Guam, Rota, Tinian, Saipan). All evidence at hand indicates that the diastrophic forces were active in the Mariana Islands throughout the Tertiary, and that they are still going on. In the Palau Islands the uplift of the Plio-Pleistocene limestones amounts to at least 700 feet (Urukthapel Islands), and in the Admiralty group, limestones presumably of the same age, have been raised at least 200 feet (Manus). The volcanic rocks upon which these limestones rest have been moderately folded and faulted, but there is no evidence of regional metamorphism in the rocks seen in either groups."

The Daito Islands in the Philippine Sea are elevated coral islands. North ("Kita") Daito Island is raised 230 feet; South ("Minami") Daito Island is raised 200 feet; and Outside ("Oki") Daito Island is raised 100 feet (Nugent, 1948, p. 979–982). According to Hanzawa (personal communication) the uplifted limestone at N. Daito Island is lower Pleistocene, and tectonic uplift probably took place in the latest Pleistocene because the limestones are only slightly weathered.

In the Pacific Basin proper, submergence has been the rule as evidenced by the drowned coral reefs, the coral atolls with thick limestones, and the guyots which almost certainly are deeply drowned islands. On Chart 6901, Fais Island, Nauru Island, and Ocean Island typical of most coral islands are the only islands which have more than the few meters of "freeboard" (Tayama, 1952). Nugent (1948, p. 983) lists Marcus Island as slightly raised, but Tayama considers it to be a sea-level coral reef. Fais Island, about 100 miles east of the Yap Trench, is a raised coral reef which has been elevated 23 meters. As pointed out, a low rise is sometimes present to the seaward of some trenches which appears to be in some manner associated with the mechanism of trench formation. Thus, uparching of the earth's crust to the seaward of the Yap Trench might account for the elevation of Fais Island although the bathymetry here is so complicated that the presence of such a rise is not certain.

Neighboring Ocean and Nauru Islands are raised 67 m and 82 m, respectively, according to Tayama (1952). This amount of elevation is too great to be accounted for by interglacial high sea levels inasmuch as estimates on the total rise of sea level, if all ice were melted, range from 24 m to 60 m (Flint, 1947, p. 437). These two isolated islands are not a part of any larger group, and they are 170 miles apart. Like the Daito Islands, they appear to have been uplifted by some regional elevation of the deep-sea floor. On the Scripps Institution of Oceanography CAPRICORN Expedition, a low ridge was discovered connecting the two islands (H. W. Menard, personal communication).

Coral Reef Problem

There has recently been a marked convergence of opinion regarding the origin of coral reefs—a result, no doubt, of the rapid accumulation of reliable data especially by drilling and by studying guyots—which has increasingly limited the realm for speculation. Of major assistance in the resolution of many aspects of the coral-reef problem has been the recognition of the different history undergone by those reefs which rest on the continental shelves, on the great geanticlinal ridges, and capping volcanoes rising from the abyssal sea floor. Chart 6901 clearly shows these differences in the structural setting of coral-reef islands.

The status of the problem has been summarized in an excellent paper by Ladd and Tracey (1949). Probably most geologists now adhere to the belief well expressed by Kuenen (1950, p. 414–479) and Tayama (1952, p. 274–276) which is a synthesis of the Darwinian concept of great drowning as the primary effect with the concept of glacial control as a secondary effect to explain many of the details of the present-day geomorphology of coral atolls. These writers also argue for extremely slow preglacial subsidence in comparison with a regional postglacial rise of sea level.

Coral reefs are sensitive "tide gauges" to past changes of sea level, and it seems that what little "freeboard" coral atolls now have is mostly due to a postglacial negative eustatic shift of sea level of 2 or 3 meters. Probably the major problem at present is the cause of the drowning. Has sea level risen or has the sea floor subsided as a whole, regionally, or as an immediate isostatic consequence to the load imposed by the reef and the extinct volcano on which it rests? The coral-reef problem, of course, is closely related to the problem of the origin of the guyots inasmuch as these are the platforms on which the Pacific Basin coral atolls rest.

Japan Sea Basin, Ryukyu Basin, and Kuril Sea Basin as Intra-Continental Basins

The Ryukyu, Japan, and Kuril arcs embrace depressions on their continental side which seem to be genetically related to the formation of the arcs. The Japan Sea Basin is by far the largest depression, extending over 150,000 square miles. It lies behind the largest arc, and it is known in the greatest detail. The Japan Sea Basin and the Kuril Sea Basin are similar geomorphic forms with an arcuate southeast side and an almost straight northwest side. They are both broad at their southwest side and become narrow to the northeast.

A "sial line" marking the boundary of the Asia continental block best can be drawn along the base of the continental slope outside the arcs extending from Kamchatka to Formosa and thence outside the Philippines and New Guinea. However, the structure of the last two named regions is too complicated to discuss here and is a portion of the East Indies structure not covered by Chart 6901. The basement geology and the submarine morphology around the Philippines has been described by Irving (1950; 1951). The basins inside the sial line—*i.e.*, inside the continental framework—might be termed "intra continental" or "hinter" basins.

Japan, of course, is a sialic block. Granite also outcrops on Kunashir Island, Urup Island, and Paramushiro Island in the Kuril Islands (Sasa, personal communication) so that the Kuril arc is probably a granitic ridge. Granite also crops out in the western Aleutian Islands, and the Bering Sea Basin is "pear-shaped" like the Japan Sea Basin suggesting that it also may be an intracontinental basin. According to H. A. Powers (personal communication) the geology of the Aleutian Islands is, in general, an extension of the Alaska Peninsula geology, and all the Aleutian-Alaska Peninsula rocks should be placed in the broad category of "sialic," even though there is a fair proportion of basaltic lava and gabbro intrusive among them. Acidic rocks are not so abundant as the basic ones, but they are widely distributed both in geologic time and in geography. Intrusive soda granite and dacite are found on Attu, dacite and rhyolite on the Rat Islands, quartz monzonite and dacites in the Andreanof Group, quartz monzonite and rhyolite on Umnak, and quartz monzonite and rhyolite on Unalaska.

Evidence shows that at least the south entrance of the Sea of Japan has been cut off in the past. Large mammals such as Pleistocene elephants have crossed into Japan indicating the existence of a land bridge. Also cold-water faunas are present in some of the Neogene strata along the west coast of Honshu suggesting that, at times, the warm Tsushima Current has not been able to enter the Japan Sea.

Niino (1935) dredged the two large banks, Yamato Tai and Kita Yamato Tai, in the Japan Sea Basin. Both banks have extensive flat tops, one at 300 m and the other at 500 m, suggesting that the banks were once islands. Rocks dredged were mostly well rounded and are of continental types resembling those found on the mainland of Japan. These highs in the basin are quite different in geomorphic appearance from those of the Pacific Basin. Terrigenous green muds and sands fill the Japan Sea Basin, and the deeper parts are smooth and featureless indicating a considerable fill of sediment (Fig. 2, Profile 7). The greatest depth is 3610 m which is about 2000 m less than the typical depth of the Pacific sea floor. The Okhotsk Sea Basin is even smoother than the Japan Sea Basin (Fig. 2, Profile 8).

Most Japanese geologists believe the major structures of Japan can be explained best in terms of a horizontal force directed from the northwest which intermittently has been active since its beginning in the mid-Mesozoic. Folding parallel to the arcuate outline of Japan and overthrusting to the southeast, such as has occurred along the Median Tectonic Line are considered evidence of such a force. It also appears likely that Japan has been shoved *en bloc* to the southeast. A crushed and shattered zone known as the Fossa Magna extends across central Honshu and normal to the arcuate outline of Japan. The Fossa Magna, which may be thought of as the "broken back" of Japan, divides the Japanese arc into a north wing and a southwest wing. The north wing appears to have moved farther than the southwest wing forming the Fossa Magna as a compressional hinge zone (Kobayashi, 1941). The obstruction to the southeastward movement of Japan, imposed by the great sea ridge extending south from Japan, also may have played a part in the formation of the Fossa Magna.

The drifting of the Japanese arc out from Asia, and the Kuril and Ryukyu arcs as well, is one way to account for the basins behind these arcs. As the sialic blocks were pushed out, exposed pools of sima would remain in the wake, and, owing to isostasy, these sima areas would be expressed topographically as basins. Accordingly, the large banks in the Japan Sea Basin may be remnant sialic blocks. The discrepancy in depth between these basins and the simatic deep-sea floor may be accounted for by sedimentation because these basins act as great sediment traps, catching detritus eroded from a large sector of Asia. It might be argued that the basins are geosynclinal waves lying behind the arcs which are geanticlinal. However, the steep flanks of the basins are more suggestive of an abrupt change in crustal structure.

Granitic cobbles are present in a Permian conglomerate in Japan although seemingly there was no granite batholith uncovered at that time. Possibly a batholith near Vladivostok was the source of the granite and Japan was adjacent to Asia at that time (Kobayashi, 1941).

CONTINENTAL SHELF AND SLOPE

Continental Shelf Sediments

The character of the bottom sediments on the continental shelf around most of Japan and in the Yellow and East China Sea has been described and charted by Shepard, Emery, and Gould (1949). Their charts show sediment distributed irregularly over continental shelves. Sand is the most common type present on the Asiatic shelf. Along much of this coast mud predominates near shore, and sand outside. Large rock areas occur particularly along the Japanese east coast where the Kuroshio flows at high velocities. Also, the wethering of volcanic rocks provides little sand, and there are few large rivers to carry sand to the Japan shelf. According to these writers, the distribution of the sediments appears to be controlled by such factors as (1) sources (large rivers, shore erosion, organic growth, and recent volcanism), (2) currents (oceanic, tidal, and longshore), (3) waves (in exposed areas), and (4) bottom topography (topographic highs, basins, and submarine canyons).

The bottom character of the shelves around Japan recently has been charted in some detail by the Japanese Hydrographic Office because of the close correlation of bottom types with fisheries.

Submarine Canyons

As elsewhere in the world, the continental slopes in the northwestern Pacific display rough topography and are incised by many submarine canyons wherever detailed surveys have been made such as around Japan and the Philippine Islands and along the east coast of Formosa. Chart 6901 is of such a small scale that only the largest submarine canyons, such as Tokyo canyon, are delineated and then only in a very generalized form. Because of the limitations of early types of echo sounders and surveying methods, only the shallow portions of the canyons are known in any detail, but it is apparent that the canyons do extend into deep water. At least around Japan the canyons appear to be incised in rock (Niino, 1952, p. 403–407) and to be similar to those off California described by Shepard (1941).

Shepard's (1948, Fig. 69, p. 210) world-distribution chart of submarine canyons shows these features only on continental and insular slopes. The Trans-Pacific Expedition echogram, however, shows at least three developed on the eastern slope of the First Honshu-Mariana Ridge more than 100 miles south of Japan. Only a single crossing was made, but the deep incisions made into an otherwise smooth slope leaves little question but that these are *bona fide* canyons. These are good examples of canyons which clearly have no relation to any landmass or even to shallow water.

As Kuenen (1950, p. 509) has pointed out, submarine canyons descend into the Japan Sea Basin to at least 1000 meters. But the sill depth of the Sea of Japan is shallow (140 meters), so that if the ocean level were lowered ponding would take place at this level, assuming an excess of precipitation over evaporation which is likely at this latitude. Thus, those persons who would explain submarine canyons by river cutting during a great withdrawal of the ocean are faced with a dilemma in the Japan Sea.

Some Japanese geologists consider that submarine canyons around Japan were formed subaerially and later submerged by marginal warping (Yabe and Tayama, 1929; Niino, 1943). The submarine canyon problem is too involved for discussion in this paper, and Chart 6901 throws little new light on the problem. In the writer's opinion, however, the submarine canyons of the northwest Pacific as elsewhere may ultimately be explained in terms of submarine processes.

Okhotsk Deep Shelf

The central portion of the Okhotsk Sea shelf is occupied by a large depressed area more than 300 miles square, immediately north of the Kuril Basin. This feature is of such grand proportions that it deserves special mention. Soundings are sparse in this region but suggest a smooth, featureless plain like a continental shelf except for its abnormally great depth averaging 1200 meters. Continental shelves of the world generally slope gently out to a depth of about 120 m where there is an abrupt increase in slope or "shelf-break", marking the top of the continental slope. Thus, the intermediate depressed region of the Okhotsk Sea is unusual. The northern portion of the deep shelf has areas deeper than 1600 meters, and it seems to be separated from the southern portion by a sill about 150 m shoaler. Also, the soundings seem to establish the 831-m shallow basin, 100 miles west of central Kamchatka, as a true basin with 500 m of closure. Because of its great extent, this deep shelf with its shallow basins must be of tectonic origin, being a subsided portion of a normal shelf.

Sounding lines show what may be cross sections of two leveed channels on the deep shelf, but this cannot be proved from the available data. Leveed channels are present on almost flat stretches of sea floor off California (Menard and Ludwick, 1951; Buffington, 1952; Dill, Dietz, and Stewart, 1954). Other probable deep-sea channels have been identified in the eastern portion of the Indian Ocean (Dietz, 1953) and in the Atlantic (Ewing *et al.*, 1953). Bottom-flowing turbidity currents with a density only slightly in excess of that of sea water may account for such channels. The Trans-Pacific Expedition fathogram shows one profile across what may be leveed deep-sea channel on the deep-sea floor east of Kamchatka.

Depth of the Shelf Break

By an examination of the original sounding sheets, an estimate was made of the depth of the shelf-break—*i.e.*, the intersection of the continental slope with the shelf. These depths are plotted on Figure 4. According to Shepard (1948, p. 143) the world average for the depth of the shelf-break is 75 fathoms or 137 m. Although there is considerable scatter from 40 to almost 300 m, this average depth holds good for the northwest Pacific.

It is a widespread opinion that the shelf-break marks the edge of a wave-built terrace formed at wave base and that the shelf edge is in equilibrium with either present sea level or a past

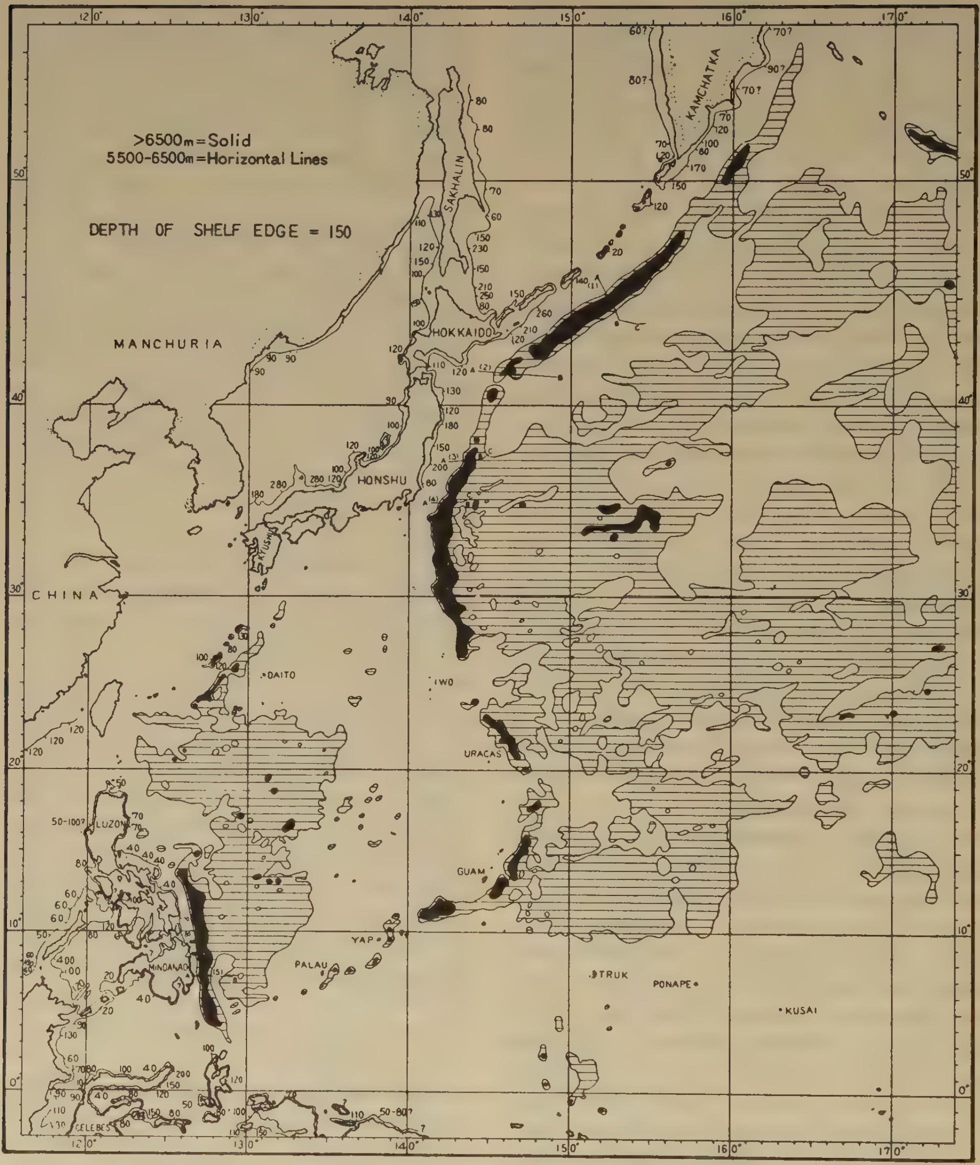
>6500m=Solid
5500-6500m=Horizontal Lines
DEPTH OF SHELF EDGE = 150
120°
130°
140°
150°
160°
170°
50°
40°
30°
20°
10°
0°
MANCHURIA
CHINA
SAKHALIN
KAMCHATKA
HOKKAIDO
HONSHU
KYUSHU
DAITO
IWO
URACAS
GUAM
YAP
PALAU
LUZON
MINDANAO
CELEBES
TRUK
PONAPE
KUSAI

Figure 4.—Simplified Depth Chart and Chart of Shelf-Break Depths

lower sea level. However, the writer thinks the shelf edge has no connnection with wave base but that its form is due to surf-zone processes at a time of lowered sea level and its present depth is due to the postglacial rise of sea level as the primary effect and to tectonic changes of earth level as a secondary effect (Dietz and Menard, 1951; Dietz, 1952). Thus, from the study of the depth of the shelf edge in general together with the study of terrace levels on the shelf it may be possible to decipher sea-level changes since the late Tertiary. When this is understood, the departure of the shelf edge depth in a particular area from the normal depth may be interpreted as a tectonic effect. In any event, the shelf-break is an important geomorphic feature deserving careful study.

Terrace levels on the shelf may indicate past

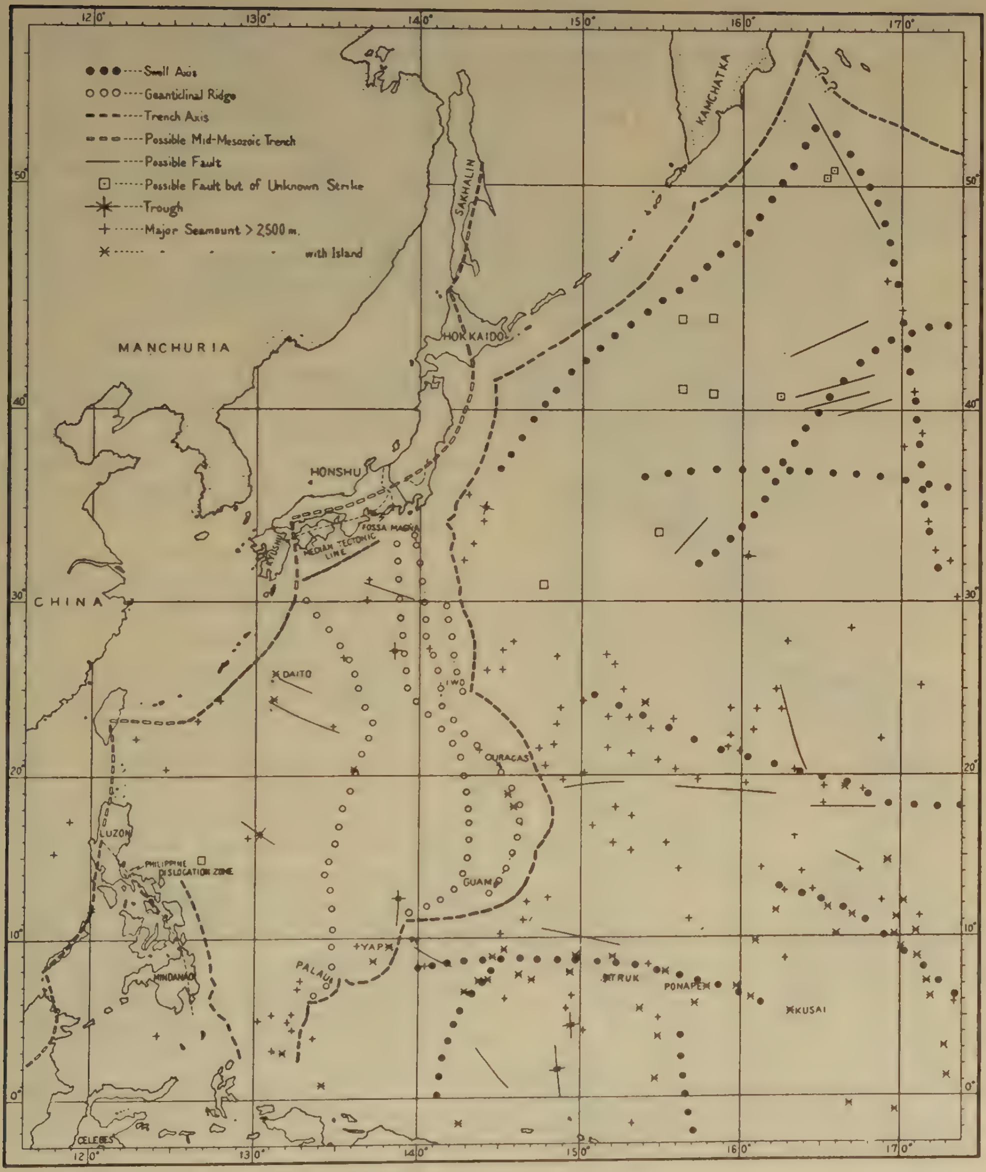
120°
130°
140°
150°
160°
170°
50°
40°
30°
20°
10°
0°
●●● ----Swell Axis
○○○ ----Geanticlinal Ridge
▬ ▬ ▬ ----Trench Axis
▭ ▭ ▭ ----Possible Mid-Mesozoic Trench
—— ----Possible Fault
⊡ ------Possible Fault but of Unknown Strike
✳ ----Trough
+ ------Major Seamount > 2500 m.
✳ ------ " " " with Island
KAMCHATKA
SAKHALIN
HOKKAIDO
MANCHURIA
HONSHU
FOSSA MAGNA
MEDIAN TECTONIC LINE
KYUSHU
CHINA
DAITO
IWO
CURACAS
LUZON
PHILIPPINE DISLOCATION ZONE
MINDANAO
GUAM
YAP
PALAU
TRUK
PONAPE
KUSAI
CELEBES

FIGURE 5.—MAJOR STRUCTURAL ELEMENTS

stands of sea level. H. Niino (Personal communication) recognizes the widespread presence of a terrace level on the shelf at minus 20 m around Japan. Such a terrace level is widely recognized in other parts of the world so that it may be related to a postglacial eustatic stand of sea level.

Around Japan Niino (1943) has collected considerable evidence that the continental shelves have been covered by shallower waters than at present and have in places been above sea level. Water-worn coarse gravel is found almost everywhere and to considerable depth. Such gravel must have been formed in rivers or in the surf zone. *Pecten tokyoensis* Tokugawa, an index fossil of the Pleistocene in Japan, has been collected as a dead shell from a depth of 120–180 m. The shallow-water fauna as-

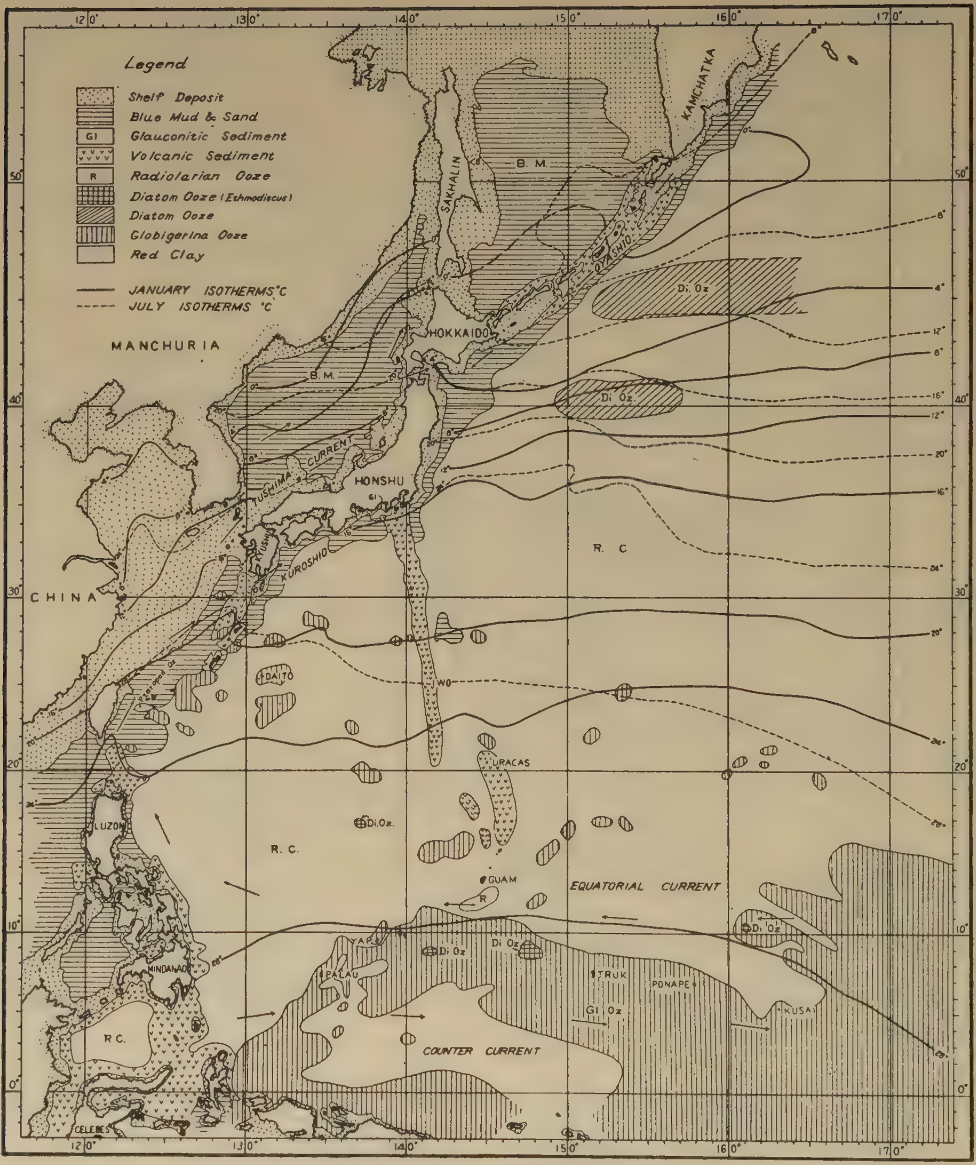
Legend
Shelf Deposit
Blue Mud & Sand
Gl Glauconitic Sediment
Volcanic Sediment
R Radiolarian Ooze
Diatom Ooze (Ethmodiscus)
Diatom Ooze
Globigerina Ooze
Red Clay
JANUARY ISOTHERMS °C
JULY ISOTHERMS °C
120°
130°
140°
150°
160°
170°
50°
40°
30°
20°
10°
0°
MANCHURIA
CHINA
SAKHALIN
KAMCHATKA
HOKKAIDO
HONSHU
KYUSHU
B. M.
OYASHIO
TSUSHIMA CURRENT
KUROSHIO
Di. Oz
R. C.
DAITO
IWO
MARCUS
LUZON
GUAM
EQUATORIAL CURRENT
YAP
PALAU
TRUK
PONAPE
KUSAI
Gl Oz
MINDANAO
CELEBES
COUNTER CURRENT

Figure 6.—Isotherm and Bottom-Sediment Chart

sociated with this fossil where it is found on land suggests that it lived in water less than 20 meters deep.

Suggestions for Future Work

Chart 6901 delineates for the first time a reconnaissance picture of the topography of about one-sixth of the Pacific sea floor. It is an important beginning which should focus attention on the deep-sea floor and stimulate research in the youthful but rapidly growing field of marine geology and geophysics.

Additional accurately positioned surveys of the sea floor are especially needed, using modern graphically recording echo sounders which obtain an essentially continuous profile of the bottom. Modern electronic equipment has now brought mapping of the deep-sea floor within the range of feasibility. Such surveys can display the profile of the sea floor in such detail as to render all previous surveys obsolete. For years to come, and until the sea-floor topography is known in considerable detail, echo sounding promises to yield the most information for the least effort and expense.

Geophysical surveys, especially gravity determinations at sea and seismic reflection and refraction work, although expensive and laborious, are much needed to solve the problems of crustal composition beneath the deep sea. Seismic studies can determine if the sima is everywhere present at a shallow depth beneath the sea floor or if layers of sial or sialsima blanket parts of the sea floor. The thickness of unconsolidated sediment can also be measured by this technique. Gravity determinations will, of course, throw light on the presence of tectogenes, the load placed on the crust by submarine volcanoes, and degree of approach to isostatic equilibrium of various regions of the ocean floor. Geophysicists also should undertake the problem of crustal yielding under a volcanic load using the data provided by those guyots which have a surrounding moat.

The successful dredging of mid-Cretaceous macrofossils and the dredging and coring of Tertiary pelagic Foraminifera from the Mid-Pacific Mountains emphasizes the importance of dredging and coring margins of the tops of seamounts. Here older rocks have not been blanketed with Recent sediment. Semi-indurated Paleocene and Eocene globigerina-ooze rocks dredged from two seamounts on the Mid-Pacific Expedition have the fresh appearance of modern material and indicate stable conditions of supersaturation of the upper waters of the tropical Pacific with respect to calcium carbonate since mid-Cretaceous. Thus, good preservation of calcareous fossil material on the sea floor appears likely in many environments. As Hamilton has showed (1953, p. 219–221) pelagic Foraminifera prove extremely useful for deep-sea stratigraphic work.

Although much bottom sampling has been done in the southern portion of 6901, there are few samples from north of 35°. Almost all the samples obtained are surface samples so that much coring needs to be done.

The Japanese have done little exploration beyond the limits of their homeland, but, with her maritime interests and her abundance of geological and geophysical talent, Japan should play a leading role in exploring the deep-sea floor of this part of the world.

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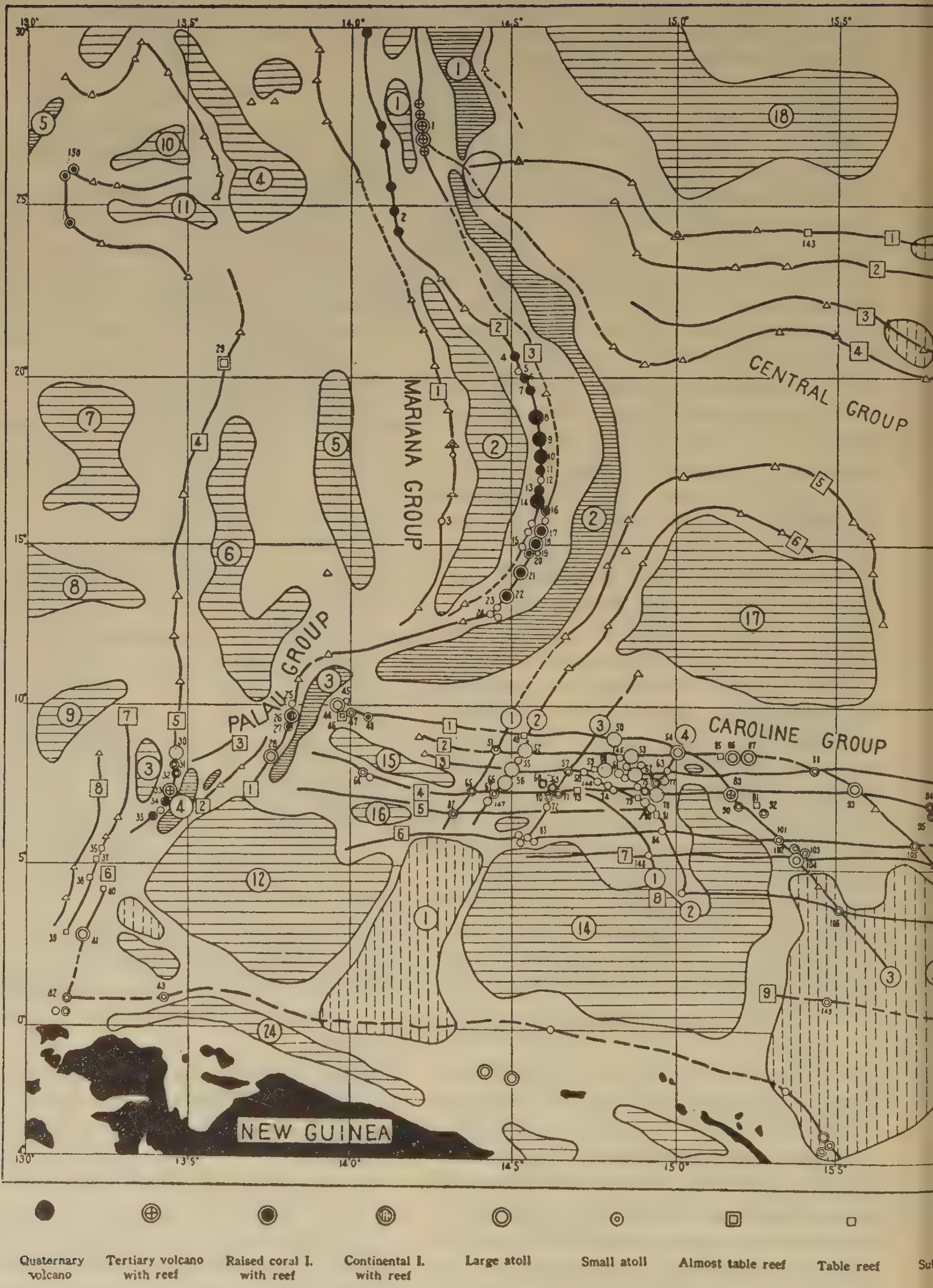
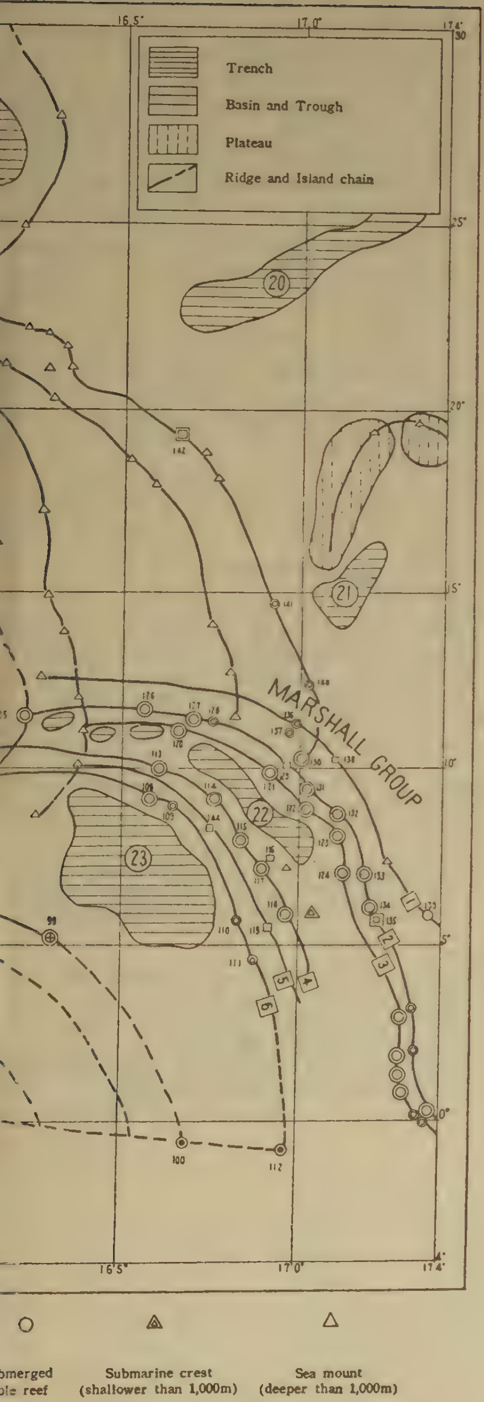

MARIANA GROUP
CENTRAL GROUP
CAROLINE GROUP
PALAU GROUP
NEW GUINEA
130°
135°
140°
145°
150°
155°
30°
25°
20°
15°
10°
5°
0°
Quaternary volcano
Tertiary volcano with reef
Raised coral I. with reef
Continental I. with reef
Large atoll
Small atoll
Almost table reef
Table reef

GEOLOGY OF THE SOUTH SEA ISLA

From Tayama (1952, Fig. 3)



Island, Reef and Bank

1 Ogasawara Is.
2 Yuō (Volcano) I.
3 Aragane R.
4 Uracas I.
5 Supply R.
6 Maug I.
7 Asuncion I.
8 Agrigan I.
9 Pagan I.
10 Alamagan I.
11 Guguan I.
12 Zealandia B.
13 Sarigan I.
14 Anatahan I.
15 Esmeralda B.
16 Medinilla I.
17 Saipan I.
18 Tinian I.
19 Tatumi R.
20 Aguijan I.
21 Rota I.
22 Guam I.
23 Galvez B.
24 Santa Rosa B.
25 Hunter B.
26 Yap I.
27 Garim I.
28 Ngulu I.
29 Parece Vela R.
30 Velasco R.
31 Ngaruangl I.
32 Kayangel I.
33 Palau I. Proper
34 Urukthapel I. etc.
35 Angaur I.
36 Fana I.
37 Sonsorol I.
38 Pulo I.
39 Tobi (Tokobei) I.
40 Merir I.
41 Helen I.
42 Asia I.
43 Mapia Is.
44 Ulithi I.
45 Falalop I
46 Losiep I.
47 Zohhouyoru B.
48 Fais I.
49 Gaferut I.
50 Mc Laughlin B.
51 Faraulep I.
52 Tarang B.
53 Mogami B.
54 Namonuito I.
55 Akasi R.
56 Earl Dalhausi B.
57 West Fayu I.
58 Oraitilipu B.
59 Pikelot I.
60 Condor R.
61 Matuye B.
62 Gray Feather B.
63 88m-B.
64 Sorol I.
65 Woleai I.
66 Gamen R.
67 Ifalik I.
68 Olimarao I.
69 Erato I.
70 Toas I.
71 Lamotrek I.
72 Orairuguron R.
73 Satawal I.
74 Condor B.
75 Puluwat I.
76 Pulap I.
77 Hitchfield B.
78 Uranie B.
79 North Manila R.
80 South Manila R.
81 Pulusuk I.
82 Eauripik I.
83 Janthe Shoal
84 Lady Elgin B.
85 East Fayu I.
86 Nomwin I.
87 Murilo I.
88 Minto R.
89 Truk Is.
90 Kuop I.
91 Nama I.
92 Losap I.
93 Oroluk I.
94 Pakin I.
95 Anto I.
96 Ponape I.
97 Mokil I.
98 Pingelap I.
99 Kusaie I.
100 Nauru I.
101 Namoluk I.
102 Satawal I.
103 Etal I.
104 Lukunor I.
105 Ngatik I.
106 Nukuoro I.
107 Ujelang I.
108 Ujae I.
109 Lae I.
110 Namorik I.
111 Epon I.
112 Ocean I.
113 Wotho I.
114 Kwajalein I.
115 Namu I.
116 Jabwot I.
117 Ailinglaplap I.
118 Jaluit I.
119 Kili I.
120 Ailinginae I.
121 Likiep I.
122 Erikup I.
123 Aur I.
124 Majuro I.
125 Eniwetok I.
126 Bikini I.
127 Rongelap I.
128 Rongerik I.
129 Jemo I.
130 Ailuk I.
131 Wotje I.
132 Maloelap I.
133 Arno I.
134 Mille I.
135 Knox I.
136 Utirik Is.
137 Taka I.
138 Mejit I.
139 Keats B.
140 Bikar I.
141 Taongi I.
142 Wake I.
143 Marcus I.
144 Lip (Erippu) I.
145 Kōyō B.
146 Tarang R.
147 Uloa R.
148 Helen R.
149 Greenwich I.
150 Kitadaitō I.

Trench

1 Japan Trench
2 Mariana Trench
3 Yap Trench
4 Palau Trench
5 Ryūkyū Trench

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DISTRIBUTION, TYPE LOCALITY, AND HABITS OF THE FISH-EATING BAT, *PIZONYX VIVESI*

BY WILLIAM G. REEDER AND KENNETH S. NORRIS

Little is known concerning the distribution of the fish-eating bat, *Pizonyx vivesi* Menegaux. The range is usually given in general terms, as "Islands and coasts of the Gulf of California, Mexico" (Miller and Allen, 1928). Considerable hunting by various field parties has failed to disclose this bat over large areas of the ascribed range. The ecological conditions at the few localities from which this species has been obtained indicate restriction to a narrow range of habitat types.

New records and distribution.—On April 24, 1949, Mr. Ed N. Harrison and party were on Isla San Jorge, off Bahía de San Jorge, in the northern part of the Gulf of California. The members of the party were still in bed at dawn when an animal was seen to alight among the rocks on the hillside several yards away. Thinking it was a petrel, the rock under which the animal had disappeared was turned over, and instead of the expected bird, a specimen of *Pizonyx vivesi* was retrieved. The prepared specimen was presented to the Los Angeles County Museum (L.A.M. 9752). It is interesting that the animal returned to its shelter so late in the morning, since Burt (1932) indicated that the bats were in their rock-slide shelters before dawn. There are some indications that such late return was unusual, since Walker (1950) stressed the predatory activity of gulls and since attempts were made by duck hawks to capture bats released by him in daylight at various points on Isla Cardonosa. No undisturbed individuals in the colony observed by Burt were seen to fly during the day.

Mr. Jay M. Savage (*in litt.*) states that this bat was described to him by natives at Punta Peñasco, Sonora, just northwest of Isla San Jorge. He also saw them fishing in large numbers off shore near Bahía de San Carlos, a short distance north of Guaymas, Sonora.

On March 25, 1951, the junior author collected two specimens at Puerto San Bartolomé (Bahía Tortuga or Turtle Bay) which establishes the presence of the fish-eating bat on the western coast of the peninsula of Baja California. A single large bat, apparently *Pizonyx*, was noted on the evening of August 14, 1952, by the junior author, from the Scripps Institution Motor Vessel, *Paolina-T*, while the ship was anchored two miles off Punta Malarrimo, Bahía de Sebastian Vizcaino, Baja California. This locality is approximately 20 miles northeast of Puerto San Bartolomé.

The localities from which specimens of *Pizonyx* have been collected are: Isla Partida; Isla Tiburon; Guaymas; Isla Pescadora; Isla San Jorge; Puerto San Bartolomé; Isla Pond; Isla Encantada; Isla Granito off Puerto Refugio on Ángel de la Guarda Island; Puerto Refugio and Isla Patos (Fig. 1). Additional sight or circumstantial records, from Isla San Pedro Nolasco, Punta Malarrimo and Bahía de San Carlos, are also mapped. A sight record from Bahía San Francisquito was received too late for mapping.

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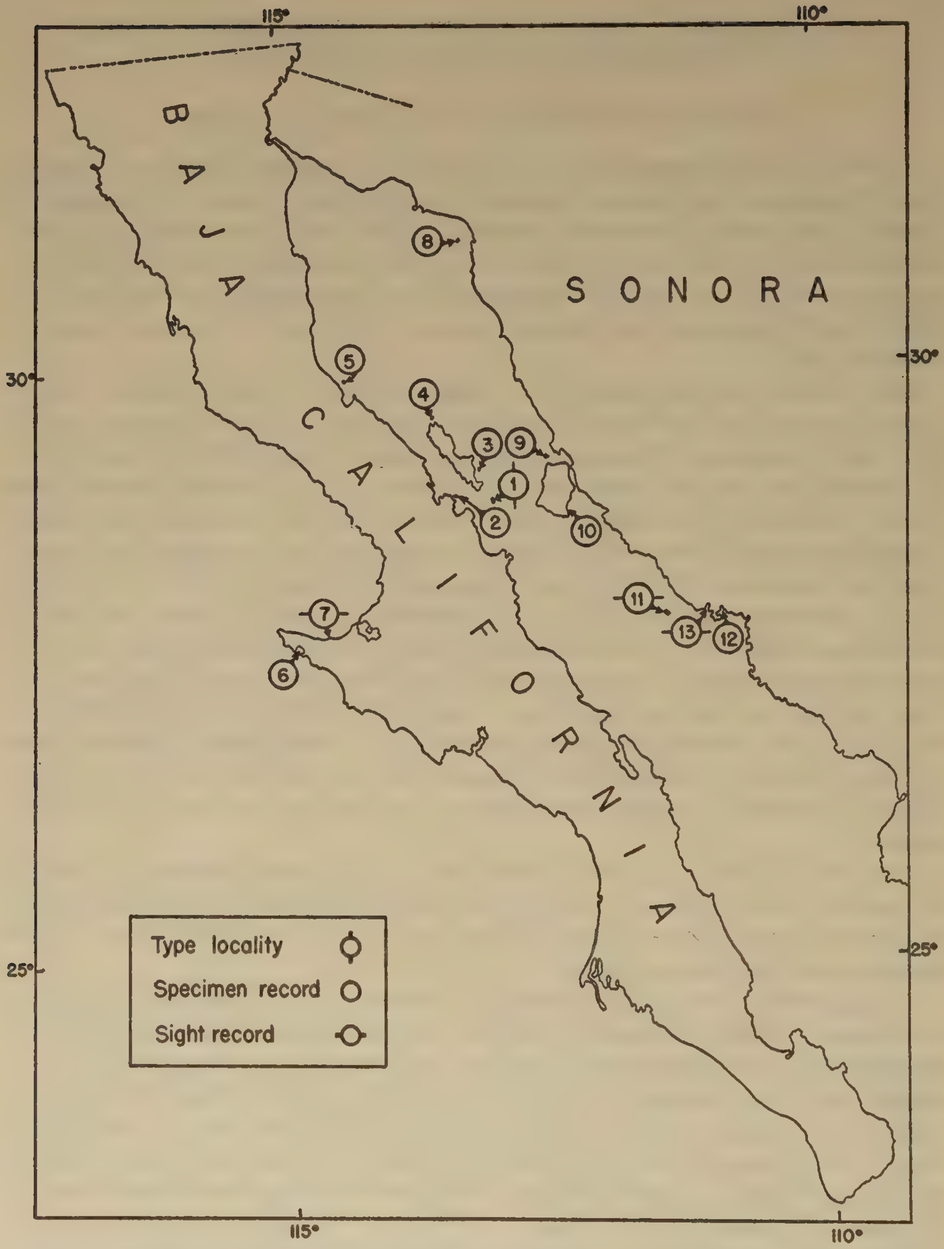
115°
110°
30°
25°
BAJA CALIFORNIA
SONORA
1
2
3
4
5
6
7
8
9
10
11
12
13
Type locality
Specimen record
Sight record

FIG. 1.—Coasts of Baja California and Sonora showing type locality, collecting localities, and sight records of the fish-eating bat *Pizonyx vivesi*. The localities are referred to by number: Baja California—1, Isla Partida; 2, Isla Pescadora; 3, Isla Pond; 4, Isla Granito, Puerto Refugio, Isla Ángel de la Guarda; 5, Isla Encantada; 6, Puerto San Bartolomé; 7, Punta Malarrimo. Sonora—8, Isla San Jorge; 9, Isla Patos; 10, Isla Tiburón; 11, Isla San Pedro Nolasco; 12, Guaymas; 13, Bahía de San Carlos. We wish to thank Mr. William L. Brudon, Museum of Zoology, University of Michigan, for the preparation of this map.

Thus the known range of the genus may be described as the coast of Sonora from the head of the Gulf of California south to Guaymas; islands of the Gulf of California from Isla San Jorge in the north to Isla San Pedro Nolasco in the south; east coast of Baja California from Bahía San Francisquito to Bahía de Los Angeles; the western coast of Baja California in the vicinity of Puerto San Bartolomé.

The following institutions or individuals have specimens of *Pizonyx*: American Museum of Natural History; British Museum (Natural History); California Academy of Sciences; Chicago Natural History Museum; Hancock Foundation, University of Southern California; Los Angeles County Museum; Mr. Laurence M. Huey; Museum of Vertebrate Zoology; San Diego Museum of Natural History; Dickey Collection, University of California, Los Angeles; University of Michigan, Museum of Zoology; United States National Museum; Muséum National d'Histoire Naturelle, Paris.

For aid in determining the records and distribution of this bat we extend grateful thanks to the following persons and institutions: Hobart M. Van Deusen, American Museum of Natural History; T. C. S. Morrison-Scott, British Museum (Natural History); Robert T. Orr, California Academy of Sciences; Colin C. Sanborn, Chicago Natural History Museum; John S. Garth, Hancock Foundation, University of Southern California; Kenneth E. Stager, Los Angeles County Museum; Laurence M. Huey, San Diego Museum of Natural History; Jay M. Savage, Natural History Museum, Stanford University; Viola S. Schantz, United States Fish and Wildlife Service; Henry W. Setzer, United States National Museum; Seth B. Benson, Museum of Vertebrate Zoology, University of California; George A. Bartholomew, Thomas R. Howell and Roy J. Pence, University of California, Los Angeles; William H. Burt, Museum of Zoology, University of Michigan.

Type locality.—The type locality of *Pizonyx vivesi* was given by Menegaux (1901) as "Ilot du Cardonal ou Islo, partie de L'Archipel Salsi puedes, au nord du golfe de Californie." The two cotypes were both originally deposited in the Paris Museum, but one is now in the collections of the British Museum.

McLellan (1927) and Miller and Allen (1928) indicate that Isla Cardonal is about 12 miles south of Isla Partida and others have repeated the statement, but there is no island in that position. Salsipuedes, the northernmost of the three islands comprising the archipelago of the same name is about that distance approximately southeast of Isla Partida. The two other islands, still farther southeast, are Isla de las Animas and Isla San Lorenzo. About six miles southeast of Isla Partida, between that island and Isla Salsipuedes, is tiny Isla Raza. Approximately nine miles northwest of Isla Partida is the southern end of the large island, Ángel de la Guarda.

In 1932, William H. Burt, in the company of J. R. Pemberton, tramped over and collected on each of the islands of this region. *Pizonyx* was found in numbers on Isla Partida, but was not collected on the other islands. Bat feces were noted by Burt on the rather distant Isla San Pedro Nolasco. Broken rock slides, the most typical habitat of this bat, were found only on Isla Partida and Ángel de la Guarda (Pl. I).

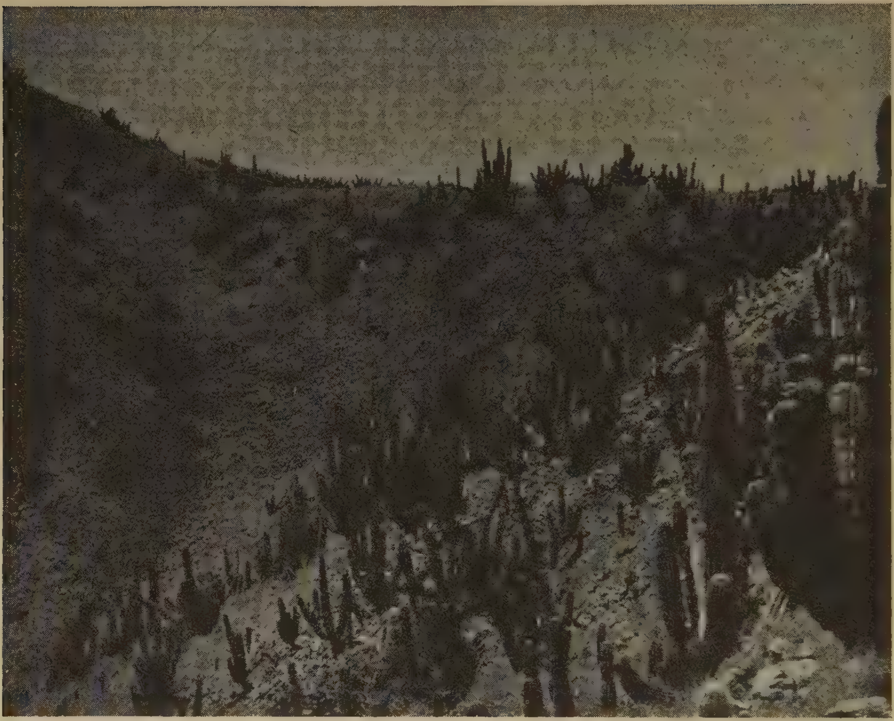

PLATE I

Isla Partida, the type locality of *Pizonyx vivesi*. Note the dense stands of Cardon cactus. Fish-eating bats were found under rocks in the slide at the left. Photograph by A. A. Allanson.

The name Isla Cardonal is obviously derived from the cardon cactus, which presumably abounds on the island for which it is the namesake. Isla Partida and Ángel de la Guarda are the only islands in the vicinity which, according to reports, support considerable stands of this large cactus.

The facts that the six islands lie in an almost straight northwest-southeast line and are roughly equidistant from the coast of Baja California indicate that although only the southern three are correctly allocated to the Salsipuedes Archipelago, any one of the six, from Ángel de la Guarda to Isla San Lorenzo might be referred to casually as a member of this series. Diguet (1912), the collector of the cotypes, never included Ángel de la Guarda in his designation of "los islotes de Sal si puedes" and this would seem to rule out this northern island as the type locality.

In the American Museum of Natural History are three alcoholic specimens, also collected by M. L. Diguet, bearing the data: "Island of Cardonal or Archangel, Northern part of the Gulf of California, October 1900." Whether the "or" reflects a question as to which of the two localities is correct or indicates a duplication of names from one island is not known. The former alternative seems the more likely, since Ángel de la Guarda has been termed "Archangel" and Diguet is known to have visited that locality as well as another that he called Isla Cardonal. In any event, it is possible that these specimens are exact topotypes, though the cotypes collected by Diguet were obtained in the month of December of the same year.

Mr. A. A. Allanson of Scripps Institution of Oceanography visited the island now known both as Isla Partida and Isla Cardonosa. Both names were applied to the same small island, though apparently the latter name, very similar in etymological derivation to the "Ilot du Cardonal" of the type description, is most used by residents of the region.

On the basis of the evidence cited above Isla Partida, at 28° 53′ N. lat., 113° 04′ W. long., the locality most prolifically inhabited by *Pizonyx vivesi* appears to be the equivalent of Ilot du Cardonal, Isla Cardonal and Isla Cardonosa, and may be regarded as the type locality. This island, readily located on modern maps of the region, is not to be confused with Isla Partida of the Espiritu Santo group, at the entrance to La Paz Bay.

Feeding habits.—On the evening of March 25, 1951, the junior author had an unusual opportunity to observe *Pizonyx* in the act of feeding. The *Paolina-T* was anchored in the nearly circular harbor of Puerto San Bartolomé (Turtle Bay), Baja California del Sur, Mexico. A flood lamp, suspended from the after boom of the ship cast a circle of light about 50 yards in radius on the water. An hour or so after sunset about two dozen large bats were noted circling in and out of this cone of light. Two, shot in flight with a .22 caliber shot pistol, were retrieved and preserved as alcoholics.

As they circled in flight, the bats periodically curled their long tails downward and forward and momentarily dipped them into the water, not rhythmically, but at irregular intervals of several seconds. One bat flew over the water holding a shining little fish in its hind feet. The stomachs of the two bats that were killed were filled with small crustacea. There was no noticeable concentration of such invertebrates in the water on this night, though a light suspended in the water attracted considerable numbers of small atherinid fishes (*Atherinops affinis*) and small anchovies (*Engraulis mordax*). George A. Bartholomew examined the stomachs of three bats captured at Puerto Refugio, Angel de la Guarda Island. Two were empty and the third contained many fragments of insects.

How these bats detect and capture their marine prey is an interesting and unsettled question. Miller and Allen (1928) and Burt (1932) speculated that the long thin recurved claws on the hind feet serve to capture small fishes or crustacea while the bat is in flight. After having observed that a single V-shaped ripple was left as these bats swooped low over the water during feeding, Walker (1950) surmised that this trail was left by the animal's chin as it cruised down to capture jumping crustaceans and believed that the claws played no part in the capture of prey. The posture of feeding bats observed at Puerto San Bartolomé was reminiscent of that of an ovipositing dragon fly; the head was held high with the tail curled forward under the animal's body. Similar behavior was described by Beebe (1941) for *Noctilio leporinus*: "Twice a bat seemed actually to seize the small fish in mid air as it jumped, but usually the position of the bat was obliquely upright, and the strong-gripping hind claws may have functioned." Gudger (1945), quoting Charles Kingsley, Gifford Pinchot, and others, indicated that *Noctilio* employs the interfemoral membranes as a scoop and possibly uses the feet as an aid in obtaining aquatic prey. The single V-shaped wake observed by Walker was obviously produced by the animal's tail and not by its chin.

The calcar cartilages, which extend inward from each hind foot into the uropatagium, no doubt hold this pouch open when the tail is dipped into the water. The flattened form of the long claws suggests that they may be dipped into the water at times during fishing, as postulated by Miller and Allen. Perhaps these claws serve primarily, as do the rictal bristles of nighthawks and poor-wills, to shunt prey into the pouch. The long, thin, and dexterous hind feet probably pick the prey from the pouch, to be eaten while the bat is in flight. How small fishes and crustaceans are detected is unknown. The bats in Turtle Bay were seen dipping their tails into the water far out into the shadowy darkness, where the light must have been very faint. Phosphorescence seemed to be absent. The irregularity of fishing movements would seem to indicate that these bats received some sensory cue from their prey and that capture is not a result of random dipping. It is interesting that these bats also catch insects, in view of the probability that methods used are different from those employed to catch fishes and crustacea.

Walker (1950) says: "From evidence that is purely circumstantial, I believe that their diet consists of small shrimp. Whole schools of these crustaceans will occasionally skim the surface when frightened, thus creating the same agitation that I saw preceding the flight of the bats. Some fish of the region also skim the surface, but as a rule their actions are due to fright from below and not from above. The white breast and underparts of these fish bats are unique for their tribe. Most of the other members of the family are a somber color which helps them to blend with the darkness. . . . The jumping crustaceans or fish would presumably see a white object approaching more easily than a dark body, and in their fright would leap from the water and become available for flying mammals." Though this mode of fishing was not observed at Puerto San Bartolomé, it may well occur when crustaceans school abundantly.

Remarks on young and on parasites.—Burt (1932) and Walker (1950) have both noted that in early June females of *Pizonyx* usually carry a single young attached to one of the two pectoral teats. Through the courtesy of Mr. Laurence M. Huey we have checked the 27 specimens, all females, collected on May 1, 1948, by Lewis Walker on Isla Pescadora. Museum notes indicate that each contained a single embryo, 10–35 mm. long.

The Puerto San Bartolomé specimens harbored many flightless dipteran ectoparasites (Nycteribiidae) of the species *Basilia pizonychus*. The identification was made by Mr. William A. McDonald, Department of Entomology, University of California, Los Angeles. No internal parasites were detected.

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of Oceanography Midpac Station 25). The complete nodule weighed about 25 grams. The air-dried sample contained 18.3 per cent water obtained at 110°C, and a 12.1 per cent residue insoluble in hydrochloric acid, consisting of a spongy network of nearly pure silica.

The red clay was collected at lat. 9°8′N., long. 144°25′W. (Scripps Institution of Oceanography Midpac Core No. 13). The sample was taken 38 to 41 cm from the top of the core. The moist specimen contained 70.4 per cent water obtained at 110°C. Lead was isolated from the entire sample.

TABLE 1.—IRON, MANGANESE, AND LEAD IN MARINE SAMPLES

Sample	Iron (Wt%)	Manganese (Wt%)	Lead (ppm)	Lead Composition (atomic ratios)*		
				Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
Lomita Marl†	0.031	0.0001	0.31	19.27	15.61	39.40
Manganese Nodule**	17.3	18.1	3,450.	18.91	15.69	38.68
Red Clay††	6.31	0.78	35.2	18.95	15.76	38.92

* The ratios have an assigned absolute error of 1%.

† Dilute acid soluble fraction. Insoluble residue = 1.5%.

** Acid-soluble fraction of composite sample, dried at 110°. Scripps No. MP 25 F2.

†† Dried at 110°, Scripps No. MP 13 38-41″.

It is believed that the similarity of the Pb/Mn ratios and the dissimilarity of the Pb/Fe ratios in the manganese nodule and the red clay indicate that a major amount of the lead in oceanic waters may be absorbed on manganese hydrosols. The compositions of the leads in the manganese nodule and red clay are similar, and both are different from that obtained from the acid-soluble fraction of the marl. This difference may indicate that the red clay and the manganese nodule, formed mainly in the sedimentary deposits of the deeper ocean, contain lead which is more nearly representative of a mean oceanic lead than that in the acid-soluble fraction of the marl which was formed in the near off-shore waters. If such is the case, the isotopic compositions of a number of marine leads, obtained from a relatively few samples in carbonate rocks of different ages, will have an unknown variation from an assumed direct correlation. This difference may, however, result from another cause. The lead from the acid-soluble fraction of the marl may be contaminated by the partial decomposition of some relatively old minerals in the insoluble residue which contain a local, or nonrepresentative lead.

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Geographic Variation in the Pacific Herring[1]

J. L. McHugh[2]

ALONG the west coast of North America the Pacific herring, *Clupea pallasi* Va- nciennes, ranges from the Bering Sea to uthern California. In the waters of Alaska and itish Columbia, this species supports com- ercial fisheries of major importance. As a nsequence, the herring has been investigated tensively, and the major features of its life story have been rather well worked out.

An important phase of early studies of varia- n in herring concerned the extent to which e stocks in the various fishing areas were dependent of each other. Since at that time satisfactory method of tagging herring was own, it was necessary to follow the methods veloped by Heincke (1898), based on studies mean numbers of vertebrae and fin rays, body proportions, growth rates and various other characters. Thompson (1917) found marked differences in mean numbers of vertebrae and anal rays in samples from British Columbia and California. Hubbs (1925) extended and confirmed the work of Thompson. Rounsefell (1930), in a thorough investigation of latitudinal variation, based on examination of a large number of samples from localities covering the entire geographic range of the species, showed that the mean numbers of vertebrae vary from 54.67 at the Shumagin Islands to 50.68 at San Diego. He was not able to demonstrate a regular latitudinal variation in mean numbers of dorsal or anal rays, although some differences were found between distant localities. Differences in head length, growth rate, size and age composition, condition, and spawning season, corroborated in general the conclusions derived from vertebral counts.

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[1] Contributions from the Scripps Institution of Oceanogra- , New Series, No. 667.

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Tester (1937a) examined a large series of samples from British Columbia waters and for this region concluded that the mean numbers of vertebrae decrease from north to south. He also found differences between localities in the mean numbers of ventral scutes, sex ratios, rates of growth in length, proportional head lengths, and age composition.

In general, these investigations appeared to have shown that the most satisfactory character for the detection of population differences in the Pacific herring was the mean number of vertebral centra. Probably for this reason the authors cited above did not make equally thorough studies of other characters. Subsequent studies on herring populations (Chapman, Katz, and Erickson, 1941; McHugh, 1942; Tester, 1949) have employed vertebral counts exclusively. In the northern anchovy (*Engraulis mordax mordax*), however, it has been found that counts of fin rays and gillrakers provide useful additional information on the population structure of the species (McHugh, 1951). Since precise enumeration of dorsal and anal rays is difficult in the clupeoid fishes (McHugh, 1951), the various investigators have hesitated to compare their counts with counts given by previous workers. Thus Rounsefell (1930) did not utilize the prior records of Thompson (1917) and Hubbs (1925), and consequently our knowledge of latitudinal variation in these characters is incomplete. Furthermore, although Schnakenbeck (1927) found that mean numbers of pectoral rays were useful in separating populations of Atlantic herring (*Clupea harengus*), Tester (1937a) appears to have been the only investigator who has studied this character in *C. pallasi*. Tester also has presented some data on the numbers of ventral scutes (keeled scales) in Pacific herring. No attention whatsoever seems to have been paid to variation with latitude in mean numbers of gillrakers.

The author has had occasion to examine many samples of Pacific herring from Alaska to southern California in a detailed study of the structure of the vertebral column.[3] Incidental to this investigation, counts of dorsal, anal, and pectoral rays, ventral scutes, and gillrakers usually were recorded. A large series of dried vertebral columns of herring from British Columbia waters was provided by Dr. A. L. Tester. Thanks are due also to Lawrence N. Kolloen of the U. S. Fish and Wildlife Service, Dr. Frances N. Clark, Julius B. Phillips, and Anita Daugherty of the California State Fisheries Laboratory, and Dr. and Mrs. Carl L. Hubbs of the Scripps Institution of Oceanography for assistance in securing samples.

SEXUAL DIMORPHISM

Tester (1937a) stated that, on the average, female Pacific herring are larger than males. Presumably it follows that the rate of growth in females is somewhat greater, although Tester (1937b) did not confirm this point. Age determinations from scales of California herring show that females are larger than males of equal age. Tester (1937a) also demonstrated statistically significant differences in sex ratio between certain localities.

No evidence of sexual dimorphism in meristic characters of Pacific herring has been reported. Analysis of data gathered during the present study has not revealed any real difference between the sexes in mean numbers of vertebral centra, dorsal, anal, or pectoral rays, gillrakers, or ventral scutes (Table I).

THE NUMBER OF VERTEBRAL CENTRA

In general, the mean numbers of vertebral centra in samples of Pacific herring decrease from north to south (Table II). Little can be added to the extensive body of data provided by Thompson (1917), Hubbs (1925), Rounsefell (1930), Rounsefell and Dahlgren (1932, 1935), Tester (1937a, 1949), Chapman, Katz, and Erickson (1941), and McHugh (1942), except to point out certain interesting irregularities in the latitudinal cline. Although the highest mean reported by Rounsefell (1930) for Alaskan waters was 54.67, this sample came from the Shumagin Islands, off the Alaskan peninsula, almost 10 degrees of latitude south of Golovin Bay in the Bering Sea, where the mean (52.79) was almost two vertebrae less. Carl L. Hubbs (personal communication) believes that Rounsefell's sample from the Shumagin Islands represents a pelagic type, either a strongly marked race of *C. pallasi* or perhaps a Pacific population of *C. harengus*. Berg (1948) regarded *C. pallasi* as a subspecies of *C. harengus*. The

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[3] McHugh, J. L. 1950. Variations and populations in the clupeoid fishes of the North Pacific. Doctoral dissertation, Univ. Calif., Los Angeles, 116 pp.

TABLE I

MEAN NUMBERS OF DORSAL, ANAL, AND PECTORAL RAYS, VENTRAL SCUTES, AND GILLRAKERS IN MALE AND FEMALE PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality and Character	Males			Females		
	Mean	Number	$\Sigma(x-\bar{x})^2$	Mean	Number	$\Sigma(x-\bar{x})^2$
Alaska:						
Dorsal rays	18.54	110	45.27	18.48	114	54.47
Anal rays	16.84	111	59.08	16.75	114	65.12
Pectoral rays	17.56	111	43.37	17.55	114	52.18
Ventral scutes	11.91	46	17.65	11.93	54	33.70
Gillrakers[1]	45.66	136	308.45	45.70	139	311.31
California:						
Dorsal rays	18.57	566	277.08	18.59	379	189.43
Anal rays	15.99	564	443.94	15.95	373	291.13
Pectoral rays	17.14	565	387.23	17.06	378	241.60
Ventral scutes	11.79	566	349.13	11.89	382	230.72

[1] Combined data from Alaska and California.

mean value most closely approaching that of the Shumagin Islands sample, from Chignik (53.33), was more than one vertebra less than this extreme value. The herring population in the White Sea, which Hubbs (1925) and others consider to belong to the Pacific species, also has a lower mean number of vertebrae (53.56) than the Shumagin Islands sample.

The low numbers reported from the Bering Sea may arise principally as a result of the low

TABLE II

THE NUMBERS OF VERTEBRAL CENTRA IN SAMPLES OF PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality	Date	Numbers of vertebral centra							Mean	Number	$\Sigma(x-\bar{x})^2$
		48	49	50	51	52	53	54			
Alaska:											
Shumagin Islands	Jul. 5, 1948	....	....	....	1	2	2	....	52.2	5	2.8
Port Dick	Jul. 11, 1948	....	....	....	1	30	54	10	52.77	95	38.91
Cape Kuliuk	Aug. 13, 1948	....	....	....	....	18	25	6	52.76	49	21.06
Bumble Bay	Aug. 6, 1948	....	....	....	....	5	16	2	52.87	23	6.61
Bumble Bay	Sept. 15, 1948	....	....	....	3	16	25	4	52.62	48	25.25
Prince William Sound	Summer 1948	....	....	....	2	34	53	8	52.69	97	40.72
McLeod Harbor	Summer 1948	....	....	....	....	13	24	3	52.75	40	13.50
California:											
Humboldt Bay	May 5, 1948	....	....	2	18	12	1	....	51.36	33	13.64
Tomales Bay	Jan. 17, 1947	....	....	7	61	31	1	1	51.29	101	42.67
San Francisco Bay	Jan. 8, 1947	....	3	36	52	15	....	....	50.75	106	56.12
San Francisco Bay	Jan. 22, 1948	....	....	39	82	13	1	....	50.82	135	51.73
Monterey Bay	January 1947	....	2	50	109	25	....	....	50.84	186	78.48
Monterey Bay	May 15, 1947	....	1	30	75	29	2	....	51.01	137	70.99
Monterey Bay	Sept. 10, 1947	....	2	30	64	15	....	....	50.83	111	49.75
San Pedro	Mar. 31, 1950	....	....	9	12	6	....	....	50.89	27	14.67
San Diego Bay	Dec. 5, 1946	1	4	54	82	16	3	....	50.73	160	95.44
San Diego Bay	Jan. 16, 1948	....	....	2	4	1	....	....	50.86	7	2.85

salinities in this region, for it has been shown that in several fishes, including *Zoarces viviparus*, (Schmidt, 1917, 1920), mean numbers of vertebrae vary directly as the salinity of the water. Barnes and Thompson (1938) reported that salinities along the Alaska coast in the Bering Sea are abnormally low due to river dilution, and LaFond and Pritchard (1952) demonstrated the striking increase in water temperature and decrease in salinity from the western to eastern Bering Sea. Chapman, Katz, and Erickson (1941) have shown that the mean numbers of vertebrae in herring from Puget Sound decrease rather markedly from the entrance to the head of the Sound. This is perhaps also a result of the decreasing salinities associated with land drainage in this region. Nevertheless, the Shumagin Islands population sampled by Rounsefell (1930) exceeds any known population of Pacific herring in mean vertebral number by an appreciable amount. This population must be extremely localized in its distribution, for a small sample of herring obtained from the Shumagin Islands in 1948 had the following counts: 51 (1), 52 (2), 53 (2), a distribution that scarcely would be expected in a sample drawn from the population sampled by Rounsefell ($t = 5.91$, P about 1 in 5×10^8).

Subsequent studies have shown that postlarval and young herring from certain localities in southern British Columbia sometimes have unusually high numbers of vertebrae. In the 1936 year-class, for example, means of 52.71 and 52.64 were encountered in two samples comprising 349 fish (McHugh, 1942). These are considerably higher than any means previously or since reported along the entire British Columbia coast. This phenomenon was reported without particular comment, for it was known that extreme tidal mixing of the waters in the southern part of the Strait of Georgia leads to relatively low water temperatures and high salinities in this area, and such conditions have been reported to produce high numbers of vertebrae (Schmidt, 1917, 1920; Tester, 1938).

Investigating populations of herring in adjacent waters off the Washington coast, Chapman, Katz, and Erickson (1941) reported equally high numbers of vertebrae in samples of adult herring from East Sound on Orcas Island. Sixty-five four-year-old fish (1933 year-class) had an average of 52.63 vertebrae, and 102 five-year-old fish (1932 year-class), 52.76. Other samples from the same general area, some taken only a few miles away, were normal for this region, having on the average about a whole vertebra fewer than the East Sound sample.

The maintenance of unusually high mean vertebral numbers in adults in regions where the species is rather abundant is surprising. Apparently the schools of herring belonging to these populations do not intermingle with the main bodies of herring in the vicinity throughout their life, or if mixture does occur, complete resegregation is effected at spawning time. Although the number of vertebrae in the Pacific herring apparently is subject to modification by environmental factors, such as temperature, during early development (Rounsefell and Dahlgren, 1932; Tester, 1938; McHugh, 1942), the degree of isolation to which these groups of fish almost certainly are subject, together with their remarkably high vertebral counts, suggests possible racial status. The high mean numbers of vertebrae found in postlarvae of the 1936 year-class in certain waters of southern British Columbia suggest that this race of herring does not necessarily spawn always in exactly the same place. Although herring schools sometimes are highly heterogeneous in composition, as shown by the recovery of tags from several different areas in one boatload of herring (Tester, 1949), it must be inferred from the evidence given above that some schools of fish remain remarkably stable throughout life. Similar evidence of an indirect nature was noted during studies of the northern anchovy (see footnote 3), when in one small sample, taken off San Diego in 1949, essentially identical abnormalities of the vertebral centra appeared at the same location on the vertebral columns of four fish in twenty-five. This phenomenon was the more striking because fusions and other abnormalities of the vertebral centra are very infrequent in *Engraulis mordax mordax*.

THE NUMBER OF PRECAUDAL AND CAUDAL VERTEBRAE

From counts made on samples of Pacific herring from British Columbia waters, Tester (1937a) concluded that mean numbers of caudal vertebrae do not vary with latitude. Thus, the decrease in mean numbers of vertebrae from north to south is confined entirely to the precaudal region. In general, this also was

Table III

Mean Numbers of Precaudal and Caudal Vertebral Centra in Samples of Pacific Herring

Locality	Numbers of fish	Precaudal vertebrae	Caudal vertebrae	Total vertebrae
Alaska:				
Port Dick	95	23.97	28.77	52.74
Cape Kuliuk	50	23.94	28.80	52.74
Bumble Bay	72	23.75	28.94	52.69
Prince William Sound	97	23.87	28.84	52.71
McLeod Harbor	40	23.82	28.92	52.74
British Columbia:				
Jap Inlet	104	23.85	28.37	52.22
Duncan Bay	215	23.71	28.62	52.33
Myers Pass	95	23.78	28.34	52.12
Deer Passage	103	23.63	28.48	52.11
Laredo Inlet	93	23.72	28.48	52.20
Kwakshua Pass	100	23.61	28.49	52.10
Smith Inlet	213	23.25	28.62	51.87
Nootka Sound	326	23.17	28.58	51.75
Barkley Sound	362	23.18	28.68	51.86
Nanoose Bay	189	23.06	28.72	51.78
Hammond Bay	81	23.21	28.48	51.69
Departure Bay	115	22.92	28.76	51.68
Dodd Narrows	98	23.16	28.63	51.79
Ladysmith Harbor	121	23.04	28.80	51.84
Mill Bay	125	23.07	28.74	51.81
Cowichan Bay	90	23.17	29.06	52.23
Swanson Channel	220	23.18	28.69	51.87
Fulford Harbor	100	23.04	28.79	51.83
California:				
Tomales Bay	101	22.31	28.98	51.29
San Francisco Bay	106	22.07	28.65	50.72
Monterey Bay	417	22.39	28.50	50.89
San Diego Bay	163	22.52	28.23	50.75

rue for young British Columbia herring, lthough the two samples with unusually high neans did not conform with this pattern McHugh, 1942). Analysis of variance of the nean numbers of caudal vertebrae in all samples erein reported from Alaska, British Columbia, nd California indicates that these samples ould not have been drawn from the same opulation (F = 4.08, $F_{0.01}$ = 1.61). However, lthough the means tend to decrease slightly rom north to south (Table III), the latitudinal rend is very irregular (Fig. 1), and the rather ighly significant F value is due largely to this pparently random variation. The average ifference in mean numbers of caudal vertebrae etween Alaska and southern California is nly 0.38 vertebra. The latitudinal trend in otal numbers of vertebrae is caused almost ntirely by a southward decrease in the numbers f elements in the precaudal portion of the ertebral column.

The relatively high mean numbers of caudal vertebrae in the samples from the 1936 year-class in Fulford Harbor and Patricia Bay, British Columbia (McHugh, 1942), further indicate the distinctness of this race of herring. The weighted mean number of caudal vertebrae (29.22) exceeds that of any other known population. A sample of postlarvae from Cowichan Bay (McHugh, 1942), representing the 1938 year-class, with 52.23 vertebral centra, was intermediate between the Fulford Harbor–Patricia Bay–East Sound race (52.70) and the typical southern British Columbia herring (51.80). If this Cowichan Bay sample were composed of a mixture of these two groups of herring, the expected mean number of caudal vertebrae would be about 28.95. Actually this sample had 29.06 caudal vertebrae, a value that does not differ significantly from expectation, suggesting that it was indeed a heterogeneous sample.

The Number of Dorsal Rays

According to Rounsefell (1930) the mean numbers of dorsal rays in samples of adult Pacific herring from Alaska to Puget Sound vary from 18.52 to 19.36. However, he found no regular trend with latitude, and concluded that populations cannot be distinguished on the

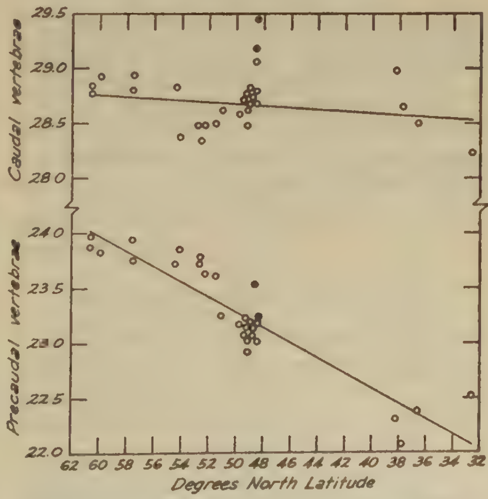

Fig. 1. Latitudinal variation in mean numbers of precaudal and caudal vertebral centra in *Clupea pallasi*. The lines have been fitted by the method of least squares. The black dots represent two samples from southern British Columbia (McHugh, 1942), and illustrate the unusually high caudal vertebral counts of the 1936 year-class in certain samples from this region. These two samples were not used in fitting the line.

basis of this character. Thompson (1917) and Hubbs (1925) reported means ranging from 18.03 to 18.42 in British Columbia and California waters.

As pointed out in a previous paper (McHugh, 1951), to obtain an accurate index of the number of rays in the median fins of clupeoid fishes, it is best to count only the principal rays. In the present study, both principal and total rays were recorded, but the condition of many of the samples was such that the tips of the anterior rays were broken, and only the total counts were considered reliable. As suspected by Rounsefell (1930), such counts on small fish may differ from those made on adults. For example, in the northern anchovy (McHugh, 1951), it has been shown that unless the rays have been stained with alizarin, the small anterior rays are sometimes missed. This is true also of the Pacific herring, for in a sample of late-stage postlarvae and small young from Humboldt Bay, California, the mean number of dorsal rays, as determined from the formalin-preserved sample, was 18.51, whereas after staining a mean count of 19.06 rays was obtained. Apparently the first unbranched ray was missed in about half the formalin-preserved specimens.

TABLE IV

MEAN NUMBERS OF DORSAL AND ANAL RAYS AT VARIOUS STANDARD LENGTHS IN POSTLARVAL PACIFIC HERRING FROM DEPARTURE BAY, BRITISH COLUMBIA

Standard length in millimeters	Mean numbers of fin rays	
	Dorsal	Anal
17	14.5	12.4
18	15.5	13.3
19	16.0	14.0
20	16.5	14.5
21	17.0	14.9
22	17.4	15.2
23	17.8	15.5
24	18.0	15.7
25	18.2	15.8
26	18.4	15.9
27	18.5	16.0
28	18.6	16.2
29	18.7	16.3
30	18.8	16.4
31	....	16.4
32	....	16.5

In a detailed study of the development of the dorsal rays in the Pacific anchovy (see footnote 3) it was concluded that the adult number of rays is not attained until the postlarvae reach a standard length of about 30 mm. Limited observations on the Pacific herring indicate that the dorsal rays are all developed at about the same standard length in this species. In British Columbia waters the young herring are about two and one-half months old at this size (McHugh, 1940). The addition of dorsal rays in two samples of postlarvae from Departure Bay, British Columbia, is illustrated in Table IV.

In a small sample from Humboldt Bay, California, ranging in standard length from 24 to 32 mm., the increase in number of dorsal rays with length is less obvious, but when these fish are divided into two lots according to standard length, the mean for the larger fish (28–32 mm.) exceeds the mean for the smaller (24–27 mm.) by 0.45 ray. A difference of this magnitude would occur by chance only once in about 100 trials. Although fish from the warmer southern waters might be expected to differentiate somewhat more rapidly than those from British Columbia, there is little evidence that the adult number of dorsal rays is formed at a standard length of less than 30 mm. in the Humboldt Bay region.

Original counts of dorsal rays are presented in Table V. The numbers of rays in adult herring from Alaskan waters compare closely with those reported by Rounsefell (1930). Although an analysis of variance suggests that the new samples from Alaska and California all could not have been drawn from the same population ($F = 4.14$, $F_{0.01} = 2.01$), there is no regular trend with latitude, and low or high mean values are about equally frequent in the northern and southern parts of the species range. There is no evidence from dorsal-ray counts that the Alaskan and California populations are distinct (Table V).

THE NUMBER OF ANAL RAYS

Rounsefell (1930) reported that mean numbers of anal rays in samples of adult Pacific herring from Alaska to Puget Sound vary from 17.31 to 16.47. He found that the mean numbers of anal rays vary irregularly with latitude, and concluded that, although statistically significant differences existed between certain localities, these differences were of un-

TABLE V

THE NUMBERS OF DORSAL RAYS IN SAMPLES OF PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality	Numbers of dorsal rays						Mean	Number	$\Sigma(x - \bar{x})^2$
	16	17	18	19	20	21			
Alaska:									
Shumagin Islands	....	....	1	4	....	....	18.8	5	....
Port Dick	....	2	37	53	7	....	18.66	99	40.32
Cape Kuliuk	....	2	24	21	3	....	18.50	50	22.50
Bumble Bay	....	5	42	23	2	....	18.31	72	29.28
Prince William Sound	....	....	3	1	1	....	18.6	5	....
British Columbia:									
Departure Bay[1]	....	1	59	113	14	....	18.75	187	65.19
Satellite Channel[1]	....	2	46	56	7	....	18.61	111	44.34
California:									
Humboldt Bay	....	2	14	15	2	....	18.51	33	12.24
Tomales Bay	....	....	32	56	4	....	18.70	92	27.48
San Francisco Bay	1	9	89	115	19	1	18.62	234	123.15
Monterey Bay	1	22	201	208	23	....	18.52	458	228.28
Salinas River[1]	....	4	22	23	2	....	18.45	51	24.63
Los Angeles Harbor	....	....	11	14	3	....	18.71	28	11.72
San Pedro Harbor	....	3	30	42	6	....	18.63	81	36.89
San Diego Bay	....	11	61	83	13	....	18.58	168	88.83

[1] Immature fish.

certain value for the separation of populations. Thompson (1917) and Hubbs (1925) indicated a decrease from north to south, ranging from 16.57 in British Columbia to 15.91 in California.

Counts of anal rays are subject to the same sources of error already described for the dorsal fin. For the Humboldt Bay sample, the mean number of rays as determined before staining was 16.24; after staining, the mean was 16.42. Hence, as also in the northern anchovy (McHugh, 1951), the error introduced by occasional omission of the short anterior ray appears to be less for the anal than for the dorsal fin.

As in the anchovy (McHugh, 1951), the adult number of anal rays does not appear in Pacific herring until the postlarvae reach a standard length of about 30 mm. or somewhat more (Table IV). The Humboldt Bay sample, composed of fish ranging from 24 to 33 mm. in standard length, showed no regular increase in number of anal rays with length, but when the sample was divided in two parts according to length, the larger fish exceeded the smaller by an average of 0.38 ray.

Original anal-ray counts are summarized in Table VI. Analysis of variance of the means of the Alaska and California samples gave an F value of 18.54 ($F_{0.01} = 2.01$). The odds are very strongly against the hypothesis that these samples were drawn from the same population. The counts reported by Thompson (1917), Hubbs (1925), and Rounsefell (1930) appear to follow this trend rather closely, and support the conclusion that the mean numbers of anal rays decrease rather regularly from north to south (Fig. 2).

THE NUMBER OF PECTORAL RAYS

Tester (1937a) found no statistically significant differences in mean numbers of pectoral rays in samples of herring from British Columbia waters. The means in samples from nine localities varied from 17.55 to 17.68.

With reasonable care, enumeration of the numbers of pectoral rays is not subject to errors caused by failure to recognize all rays. In the present investigation, the left fin was removed and the rays counted under a dissecting microscope. It must be remembered that in the clupeoid fishes, the pectoral fin rays form rather

TABLE VI

THE NUMBERS OF ANAL RAYS IN SAMPLES OF PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality	Numbers of anal rays							Mean	Number	$\Sigma(x - \bar{x})^2$
	13	14	15	16	17	18	19			
Alaska:										
Shumagin Islands	....	....	....	1	4	....	....	....	5	....
Port Dick	....	....	7	24	54	14	....	16.76	99	60.18
Cape Kuliuk	....	....	2	22	18	8	....	16.64	50	31.52
Bumble Bay	....	....	....	23	36	14	....	16.88	73	35.89
Prince William Sound	....	....	....	1	2	2	....	....	5	....
British Columbia:										
Departure Bay[1]	....	4	35	107	35	4	....	16.00	185	102.00
Satellite Channel[1]	....	....	7	40	57	6	....	16.56	110	53.05
California:										
Humboldt Bay	....	....	4	17	12	....	....	16.24	33	14.06
Tomales Bay	....	....	14	37	30	10	1	16.42	92	76.47
San Francisco Bay	....	9	45	116	52	11	....	16.05	233	176.48
Monterey Bay	1	14	96	222	106	13	1	16.02	453	327.86
Salinas River[1]	....	1	19	23	8	....	....	15.74	51	27.69
Los Angeles Harbor	....	1	7	5	11	4	....	16.36	28	34.43
San Pedro Harbor	....	....	7	26	39	8	....	16.60	80	49.20
San Diego Bay	1	12	71	67	15	....	....	15.50	166	101.50

[1] Immature fish.

late (see footnote 3), and the adult number usually is not attained until well after the transformation from postlarva to adolescent. Although it is not known exactly when the formation of pectoral rays is complete in the Pacific herring, the adult number certainly appears to be present at standard lengths in excess of 60 mm.

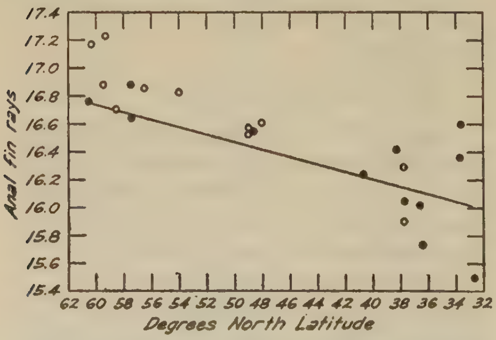

Fig. 2. Latitudinal variation in mean numbers of anal rays in *Clupea pallasi*. The line was fitted by the method of least squares. The circles, representing the data of Thompson (1917), Hubbs (1925), and Rounsefell (1930), were not used in fitting the line.

Analysis of variance of the means in Table VII shows that the samples could not have been drawn from the same population ($F = 10.88$, $F_{0.01} = 2.14$). In general the mean numbers of pectoral rays decrease from north to south (Fig. 3).

THE NUMBER OF VENTRAL SCUTES

Tester (1937a) showed that in British Columbia waters certain populations of herring may differ in the mean numbers of keeled scales (ventral scutes) lying between the bases of the pelvic fins and the anus. Variation in this character was irregular, however, and the means tended to increase from north to south.

Herring from Alaskan waters have slightly higher mean numbers of ventral scutes than herring from the California coast (Table VIII). The trend along the coast is irregular, however, for the San Diego fish had the highest mean of all samples examined. Excluding this sample, which differed widely from all others in several characters, the Alaska herring exceeded the California fish by an average of 0.20 ventral scute. This difference, 2.09 times greater than

TABLE VII

THE NUMBERS OF PECTORAL RAYS IN SAMPLES OF PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality	Numbers of pectoral rays								Mean	Number	Σ(x — x̄)²
	13	14	15	16	17	18	19	20			
Alaska:											
Shumagin Islands	....	....	....	....	....	5	....	....	18.00	5	....
Port Dick	....	....	....	1	45	48	5	1	17.60	100	42.00
Cape Kuliuk	....	....	....	1	20	28	1	....	17.58	50	16.18
Bumble Bay	....	....	....	5	33	31	4	....	17.47	73	36.17
Prince William Sound	....	....	....	....	3	2	....	....	17.40	5	....
British Columbia:											
Satellite Channel[1]	....	....	1	2	34	56	15	1	17.78	109	108.75
California:											
Tomales Bay	....	....	1	9	36	38	7	....	17.45	91	60.53
San Francisco Bay	....	....	2	40	119	62	9	....	17.16	232	140.41
Monterey Bay	....	....	5	62	245	124	21	1	17.21	458	278.46
Salinas River[1]	....	....	6	23	18	3	....	....	16.36	50	29.52
Los Angeles Harbor	....	....	....	5	14	8	....	....	17.11	27	12.67
San Pedro Harbor	....	....	1	5	16	5	1	....	17.00	28	18.00
San Diego Bay	1	0	6	69	80	10	....	....	16.55	166	85.11

[1] Immature fish.

its own standard error, could occur by chance about once in 27 trials. The unweighted mean of the British Columbia herring (Tester, 1937a) is 11.97 ventral scutes. There appears to be no regular trend in mean numbers of ventral scutes with latitude.

THE NUMBER OF GILLRAKERS

Previous workers have not discussed latitudinal variation in mean numbers of gillrakers in the Pacific herring. The most frequent number on the first arch in adults is 67 (21 + 46). Counts of rakers on the lower limb of this arch in a series of samples from Alaska, British Columbia, and California reveal no evidence that gillrakers continue to form throughout life, as they appear to do in the northern anchovy (McHugh, 1951), for no differences of great statistical significance can be demonstrated between the smaller and larger adults in the samples (Table IX). The limited data available suggest that the addition of rakers is complete shortly after the fish reach a standard length of 100 mm. (Fig. 4).

The California herring, though smaller, somewhat exceeded the Alaska fish in mean numbers of rakers (Table IX). Although the difference does not have great statistical significance (t = 1.16, P = 0.23), the smaller California fish probably did not all have the adult complement (Fig. 4). Furthermore, these southern herring have relatively larger heads, and therefore might be expected to have more rakers than those from northern waters.

FECUNDITY

Katz (1948) suggested that the numbers of mature ova in gravid females may be used to

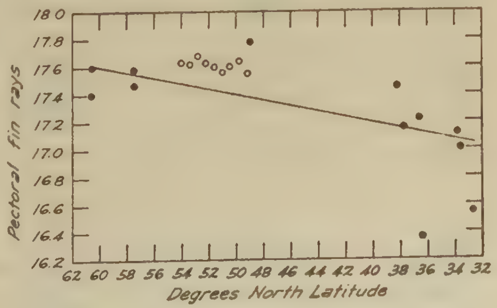

Fig. 3. Latitudinal variation in mean numbers of pectoral rays in *Clupea pallasi*. The line was fitted by the method of least squares. The circles, representing the data of Tester (1937a), were not used in fitting the line.

TABLE VIII

THE NUMBERS OF VENTRAL SCUTES (KEELED SCALES) BETWEEN THE BASE OF THE PELVIC FINS AND THE ANUS IN SAMPLES OF PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality	Numbers of ventral scutes						Mean	Number	$\Sigma(x - \bar{x})^2$
	9	10	11	12	13	14			
Alaska:									
Shumagin Islands	....	....	....	1	....	....	....	1	....
Port Dick	....	....	1	3	2	....	....	6	....
Cape Kuliuk	....	....	11	30	5	2	11.96	48	23.91
Bumble Bay	....	1	12	26	5	1	11.84	45	23.91
Totals for Alaska	....	1	24	60	12	3	11.92	100	51.36
California:									
Tomales Bay	....	3	30	40	18	....	11.80	91	56.44
San Francisco Bay	1	10	91	111	18	1	11.59	232	123.91
Monterey Bay	....	28	121	229	72	1	11.77	451	285.48
San Diego Bay	....	....	15	102	54	3	12.26	174	69.36
Totals for California	1	41	257	482	162	5	11.82	948	581.51

differentiate between populations of Pacific herring. Since the numbers of maturing ova increase rapidly with size and age, it is necessary to examine a rather large and representative series of fish to obtain a reliable estimate of the relationship.

Although estimates were made of the numbers of ova in only 17 herring from California waters, these data are presented here for comparison (Table X). The two ovaries were removed and weighed, a sample weighing about one-twentieth of the entire mass was removed and weighed, and all mature eggs in this sample were counted. An estimate of the total number was derived by a simple calculation. The much larger number of immature eggs in the ovaries was not counted, on the assumption, perhaps unwarranted, that these would not have contributed to spawning in the year of capture.

From the limited data available, the increase

TABLE IX

THE NUMBERS OF GILLRAKERS ON THE LOWER LIMB OF THE FIRST ARCH IN SAMPLES OF PACIFIC HERRING FROM THE WEST COAST OF NORTH AMERICA

Locality	Standard length in mm.	Numbers of gillrakers										Mean	Number	$\Sigma(x - \bar{x})^2$
		41	42	43	44	45	46	47	48	49	50			
Alaska	167 – 213	1	0	5	16	26	29	14	12	1	....	45.64	104	217.84
	214 – 253	....	1	4	16	26	31	17	7	1	2	45.69	105	218.25
California	101 – 141	....	....	1	4	13	6	4	2	1	....	45.58	31	53.55
	142 – 177	....	....	2	4	5	9	5	3	1	3	46.22	32	111.47
Totals:														
Small fish	101 – 213	1	0	6	20	39	35	18	14	2	....	45.63	135	271.48
Large fish	142 – 253	....	1	6	20	31	40	22	10	2	5	45.82	137	336.44
Totals:														
Alaska	167 – 253	1	1	9	32	52	60	31	19	2	2	45.67	209	436.22
California	101 – 177	....	....	3	8	18	15	9	5	2	3	45.91	63	171.43

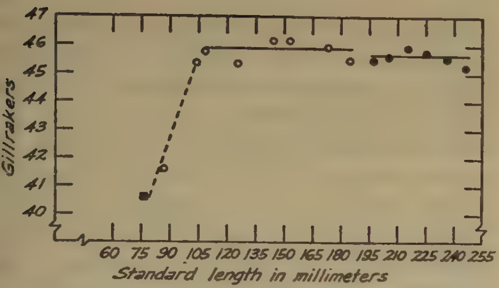

Fig. 4. Mean numbers of gillrakers on the lower limb of the first arch in *Clupea pallasi*. The formation of the rakers appears to be complete at a standard length of about 100 mm. Fish from Alaska are represented by black dots; British Columbia, black square; California, circles. The broken line was fitted by eye. The two horizontal lines represent the mean values for California and Alaska respectively.

in number of ova with increasing length of fish appears to be much less pronounced in herring from southern California waters than in the same species from the Washington coast. The smaller females had more eggs, and the larger individuals fewer, than those in the Seal Rock samples. Egg production in these relatively small California fish is approximately equivalent to the numbers reported by Hart and Tester (1934) for British Columbia herring, and Ambroz (1931) for Siberian fish, of equal size. The tendency for larger fish to produce more eggs, as demonstrated by Katz and Erickson (1950), is not especially pronounced in this small sample of California herring.

With respect to age, the California herring produce fewer eggs than herring from other localities. One fish from San Francisco Bay in its fourth year contained only 13,279 eggs, and three from the same locality in their fifth year of life contained an average of only 21,762. At the same ages the Washington herring contained 26,414 and 38,376 eggs respectively, Japanese herring 33,661 and 39,825, and Siberian herring 96,096 and 102,610. Since the Pacific herring in California waters apparently does not reach lengths as great as those reported for more northern waters, it appears that the average annual egg production per female is lower. Perhaps this is somewhat counterbalanced by an earlier maturity, or perhaps by several spawnings in a season.

TABLE X

FECUNDITY OF FEMALE HERRING FROM SAN FRANCISCO AND SAN DIEGO BAYS

Standard lengths in millimeters	Average numbers of eggs	Numbers of fish
151 – 160	18,500	1
161 – 170	15,800	6
171 – 180	18,500	5
181 – 190	22,200	3
191 – 200	20,500	2

DISCUSSION AND CONCLUSIONS

As early as 1917 it had been established by Thompson that the Pacific herring was segregated into local populations along the Pacific coast of North America. Subsequent work by Hubbs (1925), Rounsefell (1930), Rounsefell and Dahlgren (1932, 1935), and Tester (1937a, 1949), further delineated these populations and confirmed the results of meristic studies by the more direct method of tagging. These findings have been used in formulating management policies for the commercial herring fisheries of Alaska and British Columbia.

For several reasons, these investigators laid particular emphasis on the mean numbers of vertebral centra as an index of the independence of populations. By indirect methods it has been inferred that the number of vertebrae is capable of modification by temperature during early development (Rounsefell and Dahlgren, 1932; Tester, 1938; McHugh, 1942), so that in any one locality the mean vertebral number may vary from year to year. This finding, however, has not invalidated the general conclusion that the number of vertebrae decreases from north to south. The latitudinal cline is by no means regular, however, for in more than one region samples taken in adjacent areas may differ sharply. At least one of these divergent populations appears to remain isolated from its neighbors throughout life, for the mature adults differ from nearby populations equally as much as do the postlarvae. This race does not always spawn in exactly the same locality, however, and the young may sometimes intermingle with the larger native population.

Although the Pacific herring spawns normally in the intertidal zone, or at the most only a few feet below low water, occasionally eggs have been found at some depth. In East Sound, for example, Chapman, Katz, and Erickson (1941) found Pacific herring eggs in 30 feet of water.

Perhaps some factor associated with depth plays a part in determining the high mean number of vertebrae in the East Sound population, and unusually high means in other areas, such as the Shumagin Islands in Alaska. It may be significant that the Atlantic herring differs chiefly from the Pacific species by reason of the greater depth at which it spawns, and its higher mean vertebral number. If a real relationship exists between these two characters, there would be even less reason to consider these herrings distinct species.

Other than temperature and salinity, the two most obvious factors that might have pronounced effects on embryonic development at different depths are pressure and light penetration. No evidence is available on the effects of hydrostatic pressure on herring development, although Goff (1940) stated that increased atmospheric pressure retards embryonic development in *Brachydanio rerio*. However, there is some reason to believe that the number of vertebrae in fishes may be influenced by light intensity during early development. Dannevig (1932) suggested that this is true for the cod (*Gadus callarias*), and some evidence indicating an inverse relationship between light intensity and mean numbers of vertebrae has been reported for *Leuresthes tenuis* (McHugh, 1954). Thus, in relatively deep water at least three factors, namely, low temperature, high salinity, and low light intensity, may produce high mean numbers of vertebrae.

Variation with latitude in the mean numbers of vertebral centra appears to be confined, contrary to a general rule, almost entirely to the precaudal section of the axial skeleton. The mean numbers of caudal vertebrae vary irregularly with latitude, and are unusually high in the samples from southern British Columbia having high total counts. This adds weight to the conclusion that a distinct and highly homogeneous race inhabits a restricted area in contiguous waters of British Columbia and Washington.

The Pacific herring differs from the Pacific northern anchovy (McHugh, 1951) in the apparent lack of sexual dimorphism in meristic characters and of a regular cline with latitude in mean numbers of dorsal rays or gillrakers. Mean anal and pectoral ray counts, however, tend to decrease from north to south, and the mean numbers of ventral scutes, though rather irregular, tend to follow a similar trend with latitude. It also appears that, in herring of equivalent size or age, females from northern waters produce greater numbers of eggs. These findings confirm the results of the more extensive investigations of vertebral numbers, in showing that the species tends to be segregated into a series of local populations. The San Diego population, lying at the extreme southern limit of the species range, is extreme in several characters, although it cannot be separated from other populations in southern California waters on the basis of mean vertebral numbers.

Ichthyologists have long suspected that the Atlantic and the Pacific herrings (*Clupea harengus* and *C. pallasi*) may be identical, or that, at the most, their differences warrant only subspecific separation (Berg, 1948). To settle this point would require the critical comparison of large series of fish, for both species inhabit a wide geographic range, and both are notably variable in meristic characters and in body form. Two points of difference that heretofore have seemed rather distinct are the depths of spawning and the mean numbers of vertebral centra (Tester, 1946). The Pacific herring spawns usually in the intertidal zone, the Atlantic species at some depth. Developing at considerable distances beneath the surface of the water, the eggs of the Atlantic herring are subject to relatively low light intensity, high salinity, and low temperature. These extremes all tend to produce high numbers of vertebrae, a characteristic feature of the Atlantic form.

The literature also appears to show that the two species differ in mean numbers of pectoral fin rays. Tester (1937a) reported mean values ranging from 17.55 to 17.68 for British Columbia herring, and Schnakenbeck (1927) gave a range of 16.56 to 16.82 for *Clupea harengus*. The San Diego and Salinas River herring, with 16.55 and 16.36 pectoral rays, resemble the Atlantic species in this respect. Thus, two points of difference between the herrings of the two oceans are less distinct than formerly supposed.

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Three Pacific Species of "Lar" (Including a New Species), Their Hosts, Medusae, and Relationships. (Coelenterata, Hydrozoa)[1]

CADET HAND[2]

THE HYDROID "LAR," which lives as a commensal upon the tubes of sabellid polychaetes, has been described from the Atlantic by Gosse (1857) and from the Pacific by Uchida and Okuda (1941) and by Hand and Hendrickson (1950). Hincks (1872) noted that the medusae produced by *Lar sabellarum* Gosse were similar to *Willia stellata* Forbes, and later Browne (1896) clearly established that the medusa of *Lar sabellarum* was *Willia stellata*. Uchida and Okuda (1941), in their study of the Japanese "Lar," showed that their hydroid was that of the medusa *Proboscidactyla flavicirrata* Brandt and, as a result of their study together with the data of Browne and Kramp (1939), united the genera *Willia* and *Proboscidactyla*, retaining the name *Proboscidactyla* because of priority. Hand and Hendrickson (1950) described a new "Lar," *Proboscidactyla* sp., from California and suggested it might be the hydroid of the medusa *Proboscidactyla occidentalis* (Fewkes). Since 1950 the author has had an opportunity to examine medusae of *Proboscidactyla* from off the coast of Oregon, Monterey Bay, near Santa Cruz Island, and the San Diego region, the latter three localities all being in California waters. It also has been possible to obtain specimens of "Lar" from Puget Sound (Washington) and La Jolla, California. An examination of the hydroids and medusae has shown that three separate species of *Proboscidactyla* occur on the Pacific coast of the United States, a northern species (*P. flavicirrata*), a central species (*Proboscidactyla* sp. of Hand and Hendrickson 1950, named for the first time in the present report), and a southern species, *P. occidentalis*.

The definition of species in the Hydrozoa, more especially among the gymnoblasts, has long been based on rather gross, frequently ephemeral, characters such as size, shape, number and type of tentacles, arrangement of hydrorhizae, and the kinds of individuals present in the colony. In the following report, a not completely proved hypothesis has been used as one of the primary criteria of what is to be taken as a species. This concerns the nematocysts, and, briefly stated, the hypothesis is that each species of coelenterate can be identified by its possession of a unique group of nematocysts (the cnidom), at least with regard to size and shape, although not necessarily with regard to kind. This hypothesis has stemmed from the work of Weill (1934) and has proved acceptable for sea anemones as demonstrated by the numerous studies of Dr. Carlgren of Lund, Sweden. The work of E. G. Papenfuss (1936) on scyphomedusae and of F. S. Russell (1938) on hydromedusae lends much validity to the contention. To date no refutation of this hypothesis has been presented, and the study of the species of "Lar" demonstrates the further usefulness of nematocysts in the identification of hydroids. The terminology of nematocysts used herein is that of Weill (1934).

It will be noted in the following pages that the nematocysts of the hydroid stages are very similar from species to species. This, perhaps, is not unexpected as hydroids are immature

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organisms and would be expected to resemble one another more closely than the adults of different species. However, when we add the small differences in size and shape of nematocysts to the morphological differences of the hydroid stages, we find that these animals can be readily identified as separate species. The nematocysts of the medusae of these species, on the other hand, show greater differences, and again we would expect this, from the thesis that adults of related animals are less alike than their younger stages. It is, however, somewhat disappointing to discover that the medusoid and hydroid stages of a genus do not possess the same cnidom. Thus, in *Proboscidactyla* we find that the hydroids may be characterized as possessing a cnidom of three types of nematocysts (macrobasic euryteles, microbasic euryteles, and desmonemes), whereas the medusan cnidom consists of but two types (macrobasic euryteles and desmonemes). This should serve as a warning that hydroids and their medusae may not be identifiable with one another on a basis of their nematocysts. Moreover, this divergence of cnidoms in the two phases of the life history seems to imply that the nematocysts are adaptive characters which respond to environmental demands, and perhaps we should advance with caution along the road of relating larger groups such as genera and families on a basis of their nematocysts.

In the following discussion, in order to speak clearly of the arrangement of the tentacles and canals of the medusae of *Proboscidactyla*, a convention has been adopted in which the first four tentacles to develop are called *first order tentacles* and their canals are the *first order canals*. The second four tentacles arise to the right of the first order tentacles and are called *second order tentacles*. These tentacles arise at the margin of the bell at the point at which the *second order canals* join the ring canal. The *third order tentacles* are the the next eight tentacles which arise at the ends of the branches from the first and second order canals. Beyond the third order the arrangement of tentacles and canals is more difficult to discern. On specimens with 32 tentacles a rather clear *fourth order* of tentacles and canals can usually be made out, but on specimens with more than 32 tentacles the arrangement seems to have lost the regularity presented by the younger medusae. It has been noticed that, after the first order canal gives rise to the second order branch on its right and the third order branch on its left, it usually does not branch again and that most later branches arise from either the second and third order canals or from the rather diffuse fourth order.

The following material, upon which part of the descriptions presented herein are based, has been deposited in the U. S. National Museum.

1. *Proboscidactyla flavicirrata*, adult medusae, 20 specimens, U.S.N.M. 50035.
2. *P. flavicirrata*, hydroids on tubes of *Schizobranchia* and *Pseudopotamilla*, 6 specimens, U.S.N.M. 50036.
3. *P. flavicirrata*, hydroid on *Schizobranchia*, 1 specimen, U.S.N.M. 50037.
4. *Proboscidactyla circumsabella*, HOLOTYPE, adult medusa, 1 specimen, U.S.N.M. 50038.
5. *P. circumsabella*, paratypes, medusae, 8 specimens, U.S.N.M. 50039.
6. *P. circumsabella*, hydroids on *Pseudopotamilla*, 11 specimens, U.S.N.M. 50040.
7. *Proboscidactyla occidentalis*, medusae, 12 specimens, U.S.N.M. 50041.
8. *P. occidentalis*, hydroid on *Pseudopotamilla*, 1 specimen, U.S.N.M. 50042.

Proboscidactyla flavicirrata Brandt

THE MEDUSA: This medusa was first described by Brandt (1834) from the north Pacific and has subsequently been found near Japan and as far south as Puget Sound on the American side of the Pacific. Twenty-eight specimens of this medusa taken during August, 1949, have been found in plankton samples collected in the area from the mouth of the Columbia River on the north to Cape

Blanco, Oregon, on the south and at a distance of from 40 to 200 miles from shore. This plankton was collected by the Scripps Institution of Oceanography as part of its work on the California Cooperative Sardine Research Program. All the specimens observed possessed four first order radial canals and were in adult or nearly adult condition. The diameter of the bell varied from 6 to 10 millimeters and the height from 6 to 8 millimeters. They possessed from 40 to 72 tentacles.

The branching of the radial canals is very complex and highly irregular although the number of terminal branches in each quadrant is nearly equal on any given specimen. Thus, on a specimen possessing 72 tentacles, the quadrants had 17, 18, 18, and 19 tentacles, respectively. This condition is illustrated by Figure 1*g–j*. It will be noted that a canal branch does not run to each tentacle. In most specimens it appeared that the tentacles were more numerous than the canals, which condition may or may not actually exist, as the specimens examined were badly contracted and it was difficult to determine the distribution of the radial canals. In one specimen an anomalous condition was found in which the canals from two adjacent quadrants had anastomosed (Fig. 1*k*).

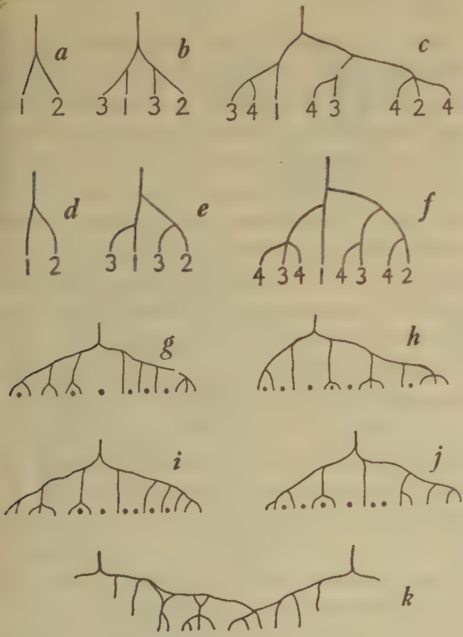

FIG. 1. *a–c*, *Proboscidactyla occidentalis; d–f*, *P. circumsabella;* and *g–k*, *P. flavicirrata*, showing (diagrammatically) the branching of the radial canals. The numbers in figures *a* to *f* refer to the order of the canals and tentacles. The spots between the ends of the canal branches in figures *g* to *j* represent the position of tentacles to which no canals could be seen to be branching.

Cnidothylacies (nematocyst sacs) are present on the exumbrellar surface and are connected to the solid ring canal by a chord of what are presumed to be endodermal cells. In many specimens no ring canal can be found, and here the chord of cells merely ends where the canal used to be. Uchida and Okuda (1941) noted that the ring canal of this species degenerates as the medusa matures, whereas Browne (1906) suggested that the disappearance of the ring canal was not unexpected, as each tentacle is directly connected to the stomach via the system of branched canals. The cnidothylacies never occur in association with the first order tentacles but can be found above all other tentacles and in the intertentacular spaces. Most specimens, however, show a somewhat irregular distribution of these structures, and the greatest number observed in any one quadrant was 14.

When this medusa is adult the gonads appear as white to creamy (formalin-preserved color) folded masses covering most of the stomach. The four gonadial masses present occupy interradial positions, each mass being developed as a pair of thickened lobes upon the adradial sides of the quadratic stomach with a thin sheet of gonadial tissue connecting the two lobes and covering the stomach wall. The gonads do not appear to fuse across the radial margins of the stomach. The lips of the manubrium are highly folded and hang but a short distance below the oral end of the gonads. Figure 2 illustrates the several features just mentioned.

The tentacles, which are inserted into the bell margin by endodermal bulbs, were quite contracted in most specimens; however, it was immediately apparent that the older tentacles are somewhat longer and larger than the younger ones. The tentacle bulbs are light yellow to cream in color and much more opaque than the tentacles.

The shape and general appearance of the medusa is shown in Figure 2, although only one quadrant is shown with all its details. It will be noted that there are four interradial, subumbrellar pouches which extend the subumbrellar cavity well above the level of the stomach. This is a characteristic of all three of the species described in this paper.

The nematocysts of the genus *Proboscidactyla* are known for the hydroid in two instances (Russell, 1938; Hand and Hendrickson, 1950) and in one case for the medusa (Hand and Hendrickson, 1950) and in this latter case only for very immature medusae. The nematocysts of adult *P. flavicirrata* were studied, and a simple cnidom of two types was found as follows:

Cnidothylacies

Macrobasic euryteles...	22—30×9—14μ
Desmonemes.........	5— 7×4— 6μ

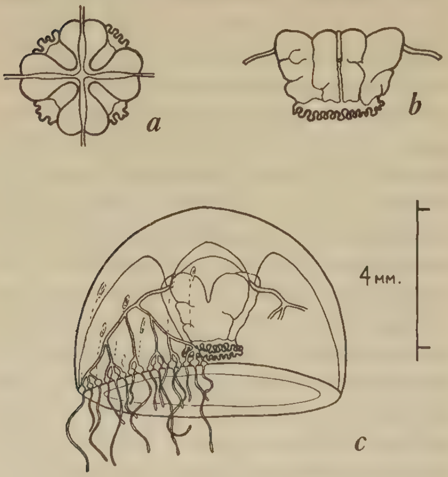

FIG. 2. *Proboscidactyla flavicirrata. a*, Aboral view of the stomach; *b*, side view of stomach; *c*, whole medusa with only one quadrant shown in detail.

Tentacles

Macrobasic euryteles...	8—12×5— 7μ
Desmonemes.........	5— 7×4— 6μ

Figure 3*a–c* illustrates the nematocysts. The desmoneme of the cnidothylacies appears to be identical to that of the tentacles.

THE HYDROID: Uchida and Okuda (1941) have given a rather complete description of this hydroid, although a few additional remarks and comparisons of their report with material from Puget Sound seems desirable. Several colonies of this hydroid were collected during the summer of 1950 in Puget Sound by Dr. Ralph I. Smith of the University of California at Berkeley and were given to the author for study. Detailed notes and sketches of the appearance and color of this hydroid in life were also gratefully received from Dr. Smith.

The organization and arrangement of individuals in *P. flavicirrata* are quite different from those of the other Pacific species. The gastrozooids and gonozooids stand in a double row or ring around the lips of sabellid tubes with the gastrozooids innermost, while the naked hydrorhizae tend to form parallel rows extending several millimeters along the long axis of the worm tube with occasional random anastomoses. The gonophores may arise either from the hydrorhiza near the base of an adjacent gastrozooid or actually from the proximal portion of the gastrozooid (Fig. 4*b*, *c*). What are presumed to be young or abortive gonozooids may occasionally be found at almost any point among the hydrorhizae, although they were not as numerous as those found by Uchida and Okuda. Where young or new gonozooids are forming on the bases of the gastrozooids, the appearance is that the gastrozooid is growing a tail (Fig. 4*a*). Figure 4*b* illustrates the general appearance and organization of a colony.

A total of 16 colonies was observed, and of these seven showed strongly parallel hydrorhizal nets and the remaining nine varied from a reasonably close approach to parallel

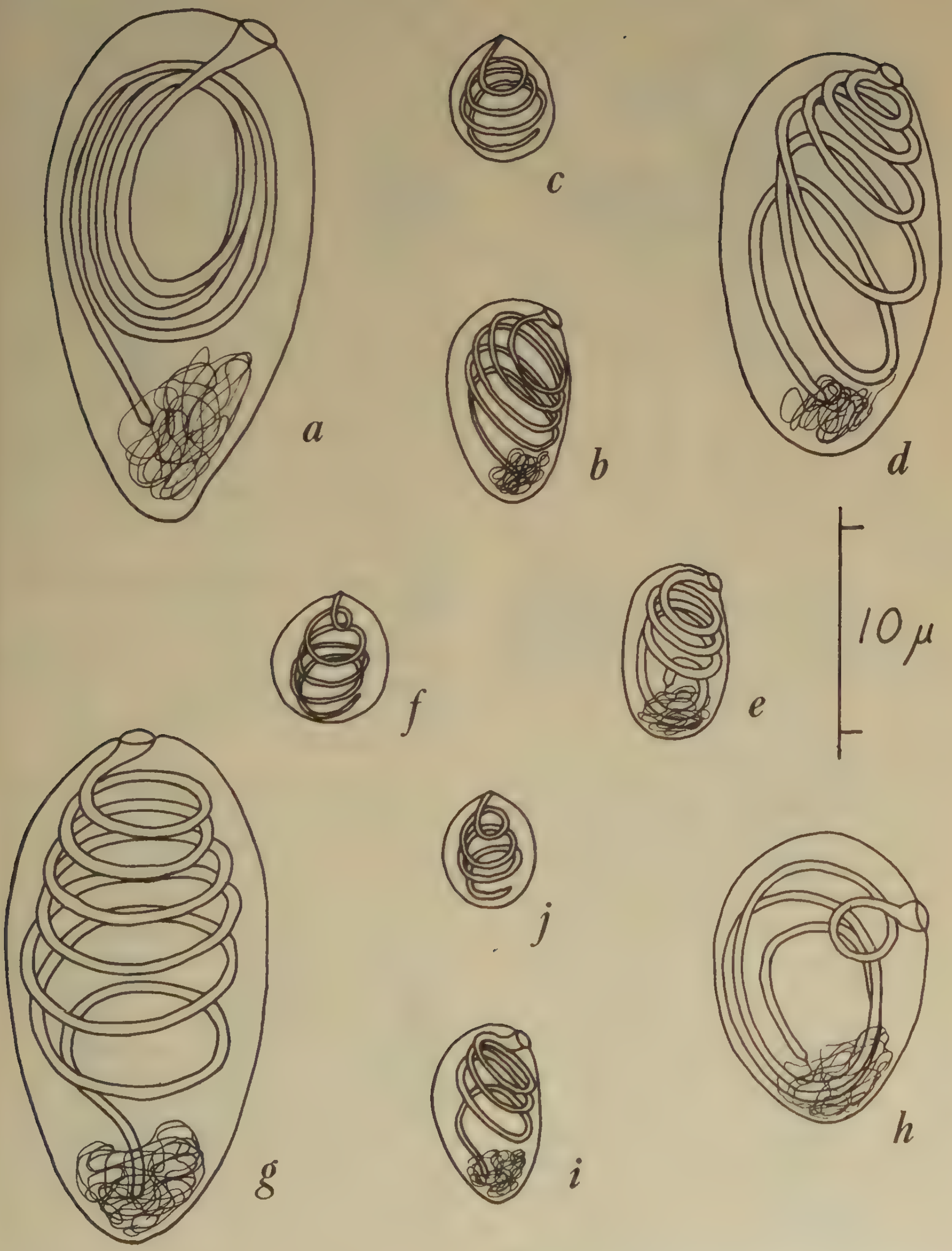

FIG. 3. The nematocysts of the medusae. *a–c, Proboscidactyla flavicirrata; d–f, P. circumsabella; g–j, P. occidentalis. a, b, d, e, g, h, i* are macrobasic euryteles; *c, f, j* are desmonemes.

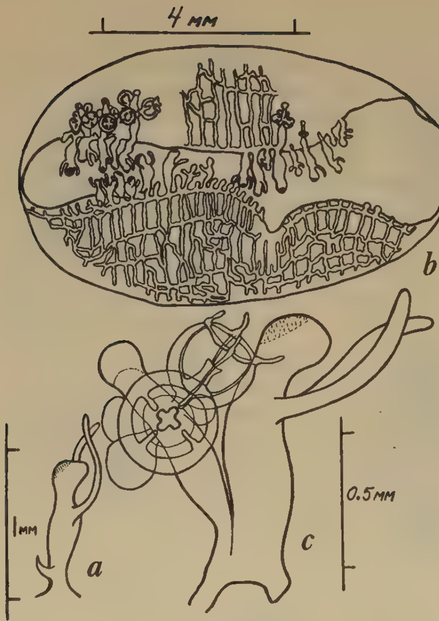

FIG. 4. The hydroid of *Proboscidactyla flavicirrata*. *a*, Young gastrozooid with a "tail"; *b*, a colony, only part of which is shown, as seen by looking down upon the end of a worm tube; *c*, gastrozooid and gonozooid, the latter with several medusa buds.

networks to very random, irregular networks. It was noted that the nine colonies showing the less parallel hydrorhizal networks also possessed very slightly smaller gastrozooids than the other seven colonies and that these nine colonies were the only ones possessing scattered gonozooids or no gonozooids at all. Some of these colonies were obviously immature, whereas others were quite mature. It was thought that these nine colonies might be of some other species, but this idea was discarded as no differences between these and the larger colonies could be found in their nematocysts. So far no one has demonstrated whether a single colony of "Lar" produces only one sex of medusa or whether both sexes can be produced by a single colony, so the suggestion may be tentatively put forth that the visible morphological differences in the Puget Sound "Lar" may be of a sexual nature.

The color of this hydroid in life is, in general, orange to pink with the color restricted to the endoderm as in other species. The gastrozooids are 0.8–1.2 millimeters tall by about 0.2 millimeter in diameter. The gonozooids are in general thinner and slightly shorter than the gastrozooids. Two tentacles are present on the gastrozooid and none on the gonozooid. The size of the Puget Sound individuals is slightly larger than that of those from Japan, and no variation in tentacle number was noted, whereas a number of specimens with extra tentacles was reported from Japan. The Puget Sound "Lar" possessed from two to eight medusa buds, commonly eight, with four of the buds large and well developed and four as small, poorly developed medusae. The four small buds alternate with the four large ones, and all buds seem to arise at a single level slightly above the middle of the gonozooid.

The nematocysts of the hydroid are as follows:

Macrobasic euryteles.....	17—25×8—12μ
Large microbasic euryteles	10—18×4— 6μ
Small microbasic euryteles	5— 6×2— 3μ
Desmonemes...........	3— 5×2— 4μ

The tentacles of the polyps seem to possess only the small microbasic euryteles listed above, whereas the three remaining types were found in the caps of the polyps. The desmoneme and the large microbasic eurytele also occur in small numbers over the surfaces of the polyps. Figure 5*a–d* illustrates the appearance of the nematocysts of this hydroid.

THE HOSTS: Uchida and Okuda (1941) reported this species upon the sabellid, *Potamilla myriops*. Berkeley and Berkeley (1952) do not list this species for the Puget Sound area but do list *Potamilla neglecta*, which is one of the hosts for *Proboscidactyla occidentalis*, the third species of this report. *Proboscidactyla flavicirrata* occurred on two species of sabellids in the Puget Sound area, namely *Schizobranchia insignis* and *Pseudopotamilla ocellata*. Ten genera of sabellids were reported by

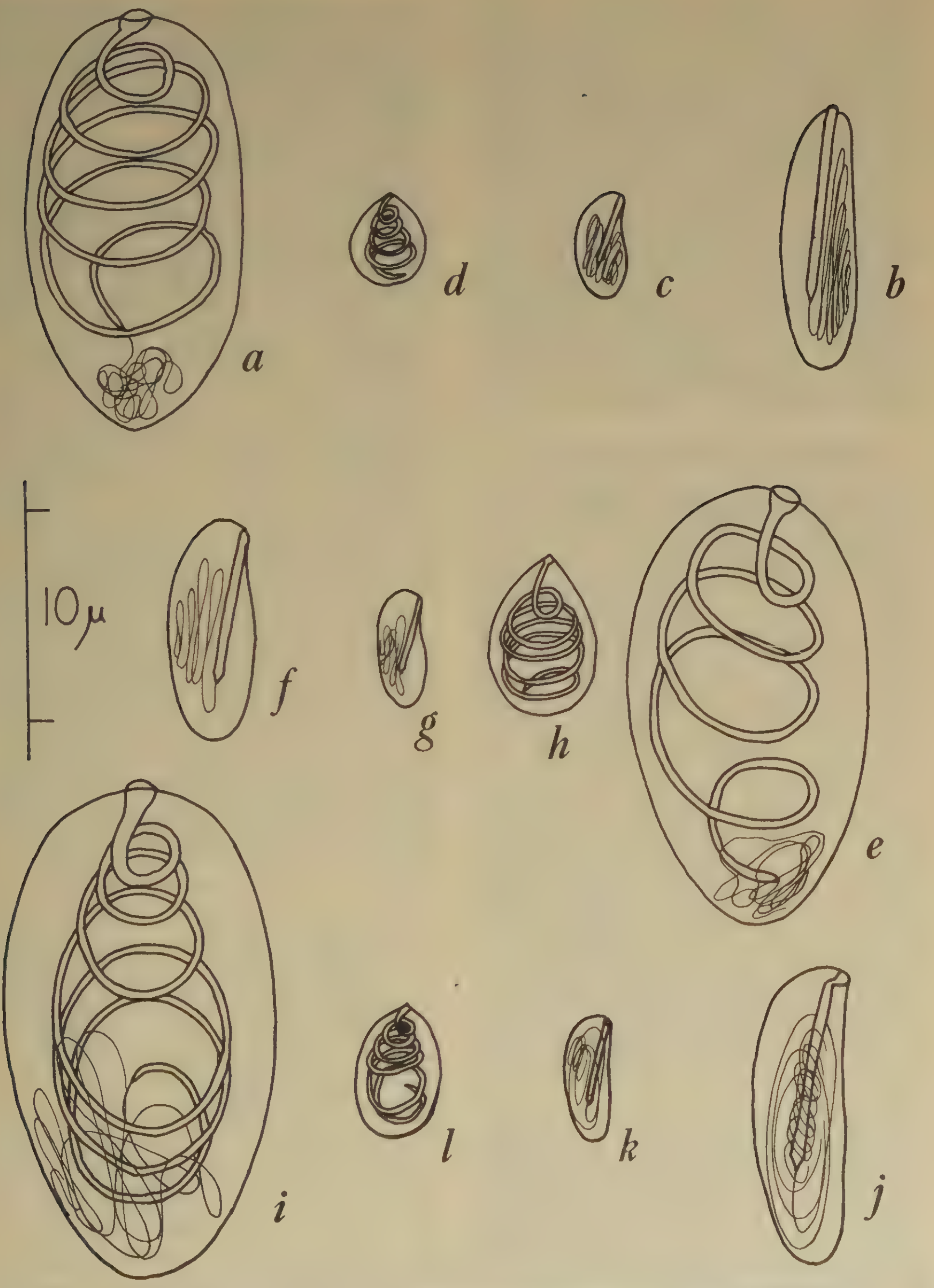

FIG. 5. The nematocysts of the hydroids. *a–d*, *Proboscidactyla flavicirrata*; *e–h*, *P. circumsabella*; *i–l*, *P. occidentalis*. *a*, *e*, *i* are macrobasic euryteles; *b*, *c*, *f*, *g*, *j*, *k* are microbasic euryteles; *d*, *h*, *l* are desmonemes.

Berkeley and Berkeley (1952) from the Pacific area around Puget Sound, with a total of 19 species involved. It seems likely that further observation will reveal the presence of this hydroid upon still more sabellids than the three from which it has been reported to date.

The observed difference in size of individuals and in colony morphology reported in the description of this hydroid does not seem to be correlated with the host upon which the colony is growing. Colonies with both parallel and irregular hydrorhizal nets were found upon both of the sabellids reported above as hosts for *Proboscidactyla flavicirrata* in the Puget Sound area.

Proboscidactyla circumsabella sp. nov.

The hydroid and young medusa of this species were first described by Hand and Hendrickson (1950) under the name of *Proboscidactyla* sp. Since that description appeared, a series of medusae of this species ranging from small immature specimens to adults have been obtained from plankton from Monterey Bay. I am indebted to Mr. Frank Gwilliam and Mr. Meridith Jones of the University of California at Berkeley for some of these specimens.

As the hydroid and young medusa have already been described, it does not seem necessary to repeat the whole diagnosis at this time, but certain salient features are worth repeating for the sake of comparison with the other two species considered here.

THE MEDUSA: Adult medusae were collected during the months of June and July, 1951, and a single specimen during July, 1952. A total of nine adult medusae have been examined.

The largest specimen observed measured 3.0 millimeters, bell diameter, by 2.5 millimeters high. This specimen possessed 32 tentacles and 28 cnidothylacies. The gonads were well developed and occurred in the interradial position as four paired masses of simple swollen lobes on the adradial sides of the stomach. Figure 6*a–c* illustrates the appearance of a living, 24-tentacled, adult medusa as well as the details of the shape and location of the gonads and the lips of the manubrium. The manner in which the lips fold seems to be characteristic of this species.

From a study of the nine medusae in hand, it appears that a rather regular system of branching of the radial canals obtains in this species, with the result that the adult medusae are quite uniform. Of the specimens examined only a single one deviated from the pattern of development presented in Figure 1*d–f*. This single specimen possessed 25 tentacles, the single unusually located tentacle occurring to the right of the second order tentacle of one quadrant and connected to the second order canal by a short canal of its own. In immature or developing medusae there is an obvious difference in tentacle length, tentacle bulb diameter, and radial canal size; the older tentacles, tentacle bulbs, and radial canals are longer or larger, and thus the developing complexity of the canal system is readily visible. From the time the medusae reach the 16-tentacle stage until they attain the 32-tentacle condition the exact order of appearance is not precise; therefore, specimens may have odd numbers of tentacles, although the end result is uniform as judged by the four specimens which possessed 32 tentacles.

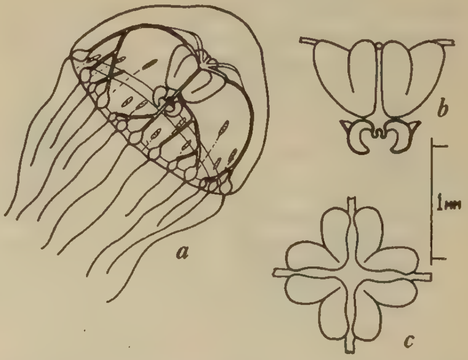

FIG. 6. *Proboscidactyla circumsabella*. *a*, Whole medusa, with tentacles shown on one half only; *b*, side view of stomach; *c*, aboral view of stomach.

In life this medusa is nearly colorless, pigment being restricted to the tentacle bulbs and the wall of the stomach. These areas are brown to orange brown. The tentacle bulbs appear to develop before pigment is deposited in them so that the small tentacle bulbs are colorless or nearly so. The older tentacle bulbs are usually a bright orange-brown color. The gonads are very lightly colored, those of the males being white and of the females a light creamy color. The sexes are separate.

The nematocysts of adult *P. circumsabella* are as follows:

Large macrobasic euryteles	17—26×8—12μ
Small macrobasic euryteles	7—10×4— 5μ
Desmonemes	5— 7×4— 6μ

The large macrobasic euryteles are restricted to the cnidothylacies, whereas the small macrobasic euryteles occur in the tentacles. The desmonemes are present in both the tentacles and cnidothylacies. The large macrobasic euryteles occur in very small numbers, and not all cnidothylacies were found to possess them (Fig. 3*d–f*).

THE HYDROID: The hydroid is similar to other species of *Proboscidactyla* in that the colony possesses two major types of individuals, the two-tentacled gastrozooids and the gonozooids, which are without tentacles and bear the medusa buds. Small gonozooids or dactylozooids occur at the margins of the hydrorhizal network. The gonozooids occur as scattered individuals arising from the hydrorhizae and are never arranged in a row immediately behind or on the gastrozooids, as in *P. flavicirrata* or *P. stellata*. Up to a maximum of four medusa buds may be borne upon a single gonozooid. The individuals of a colony seldom are as much as 1 millimeter tall and are commonly about 0.8 millimeter tall by about 0.1 millimeter in diameter. The hydrorhizal network is devoid of any covering and may form extensive anastomosing nets running along the tube for as much as 15 millimeters.

The nematocysts of the hydroid are as follows:

Macrobasic euryteles	16—24×9—12μ
Large microbasic euryteles	9—12×3— 4μ
Small microbasic euryteles	5— 6×2— 3μ
Desmonemes	6— 8×3— 4μ

The macrobasic euryteles occur only in the cap of the gastrozooid and the tip of the gonozooid. The other three types of nematocysts occur in most areas of the gastrozooid and gonozooid although no small microbasic euryteles were found in the gonozooids. Figure 5*e–h* illustrates the nematocysts of the hydroid.

THE HOSTS: *Proboscidactyla circumsabella* occurs most commonly on the sabellid *Pseudopotamilla ocellata*. Careful observation of other sabellids, such as *Eudistylia polymorpha* and *Sabella media* which sometimes occur with *Pseudopotamilla ocellata*, have failed to reveal the presence of a single "Lar" on the tubes of these other worms. This may be due to the fact that these worms commonly grow to a considerably larger size than the common host and are for this reason an unsuitable substrate. Other sabellids, such as *Myxicola* and *Eudistylia vancouveri*, have tubes whose consistency or structure make it impossible for this hydroid to live upon them. Of the several different sabellids examined from Monterey Bay and vicinity only a single example of "Lar" upon any host other than *Pseudopotamilla ocellata* has been found, and this was a small colony on the tube of *Pseudopotamilla intermedia*. This worm had built its tube of elongate, rather pointed, sand grains and presented a much more irregular substrate to the hydroid than the tubes of its regular host. It appears that *Proboscidactyla circumsabella* is limited to hosts whose tubes do not reach very large sizes, whereas *P. flavicirrata* may be found upon tubes up to about 1 centimeter in diameter. The largest worm tube upon which *P. circumsabella* has been found was about 4 millimeters in diameter.

Proboscidactyla occidentalis (Fewkes)

In 1889, Fewkes described a medusa, *Willia occidentalis*, from near Santa Cruz Island. From his description it is clear that this medusa is a *Proboscidactyla*, and, moreover, it is presumed that this species is identical to that found at La Jolla, California, because a single specimen collected in 1950 near Santa Cruz Island is identical to the more abundant La Jolla material. Thirty-one medusae with 8–40 tentacles have been examined from the San Diego area, as well as a single 28-tentacle specimen from Santa Cruz Island plus 18 colonies of a hydroid which have been assigned to this species. The hydroids were found on sabellid tubes which were associated with a kelp holdfast. This kelp holdfast was growing in 40 to 50 feet of water and was obtained by Conrad Limbaugh on April 12, 1952, while diving with an aqua-lung at La Jolla. The samples from which the medusae were obtained were collected by Conrad Limbaugh, Robert Bieri, and John Bradshaw, of the Scripps Institution of Oceanography.

THE MEDUSA: Medusae of this species have been found in plankton samples collected at Santa Cruz Island in the month of March, 1949, and from La Jolla and San Diego Bay during the months of March through July, 1952. The largest medusa collected was a female 3.5 millimeters high by 3.5 millimeters in diameter. This medusa possessed 40 well-developed tentacles. The smallest medusa was slightly greater than 1 millimeter in height and diameter and possessed eight tentacles. In life little pigment is to be seen on these medusae, except for the dark reddish-brown to black bulbs of the tentacles. Some specimens show a little light-brown pigment in the stomach walls.

The gonads are apparent on 8-tentacled medusae but do not begin to bulge from the adradial walls of the stomach until about the 16-tentacle stage. The gonads appear ripe at the 32-tentacle stage, and the female possessing 40 tentacles seemed to have shed part of the eggs from one quadrant of the gonads. As in the other species of *Proboscidactyla*, the gonads do not fuse across the radial margins of the stomach and are disposed as four interradial masses consisting of paired adradial lobes connected at the interradii by thin sheets of gonadial tissue. The gonads, when fully ripe, show folds along their medial surfaces. The sexes are separate.

The manubrium is very short and the lips are highly folded. This species closely resembles *P. flavicirrata* in this respect.

The radial canals branch, and the general pattern and order of development is presented in Figure 1*a–c*. Small variations in the location and length of the branched canals occur from quadrant to quadrant and specimen to specimen; however, the order and final arrangement seems to be relatively definite so that when the 32-tentacle stage has been reached a difference in pattern of branching is apparent when it is compared with the same stage of *P. circumsabella*. This difference consists of a pair of fourth order tentacles spanning the second order tentacle in *P. occidentalis*, whereas in *P. circumsabella* a pair of fourth order tentacles span the left hand third order tentacles (compare Fig. 1*c* and 1*f*).

In the figure of this species in Fewkes (1889) a 20-tentacle medusa is shown. This is presumably a fleeting stage in development in which the first of the fourth order tentacles had appeared. The radial canals shown in Fewke's figure represent a condition seldom attained in this species in that he has shown the canal branched into three equal parts, with each of the lateral branches possessing another branch. The manner in which the canals of all species of *Proboscidactyla* branch is such that this is nearly an impossibility. It is presumed that Fewkes drew a symmetrical diagram which was not a copy of the actual pattern present. It will be noticed, if one compares the figures of the three species of this report showing the systems of branching canals, that *P. occidentalis* and *P. flavicirrata* tend to present a pattern in which the primary radial canal of each quadrant bifurcates rather symmetrically, whereas in *P. circumsabella* the primary canal seems to run directly to the margin, giving off its branches laterally. This difference is not absolute but applies in most specimens.

A ring canal was present in most of the individuals observed, although the specimens possessing 32 or more tentacles did not show this structure. The disappearance of the ring canal seems to be a characteristic of adulthood of this genus.

The bell of this species is somewhat thicker then that of the other two species, and, also, the tencency for the height to be the same as, or greater than, the diameter is striking. In preserved specimens the adoral end of the stomach never is located more than half the distance from the velar opening to the adoral tip of the bell (see Fig. 7). Fewkes (1889) described a slight constriction in the external outline of the bell at a level with the base of the stomach and showed this constriction in his figure. This constriction was apparent in two of the 31 specimens examined but apparently is not characteristic of the species. More commonly the bell is hemispherical or is of an elongate shape such as could be depicted by a figure representing slightly more than half of an oval.

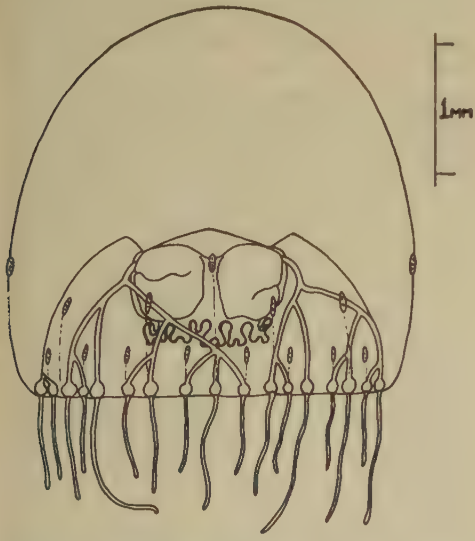

FIG. 7. *Proboscidactyla occidentalis*. Whole medusa with tentacles shown on one half only.

The nematocysts of the medusa present a familiar pattern. Only two kinds, macrobasic euryteles and desmonemes, are present, but a rather unusually shaped medium-size macrobasic eurytele occurs in the cnidothylacies. This nematocyst (Fig. 3*h*) is distinctive of this species. In the tentacles a more usual, small, macrobasic eurytele is numerous, as are desmonemes. The nematocysts of this species were found to be as follows:

Cnidothylacies	
Large macrobasic euryteles	24—28×11—14μ
Medium macrobasic euryteles	12—17× 8—12μ
Desmonemes	5— 6× 4— 5μ
Tentacles	
Small macrobasic euryteles	7—10× 4— 5μ
Desmonemes	5— 6× 4— 5μ

Figure 3*g–j* illustrates the nematocysts of this species.

THE HYDROID: The hydroid stage of this species resembles in its general form that of other known species, its most singular character being that the gonophores bear large numbers of medusa buds which were not discerned to have a regular arrangement upon the gonophores. A maximum of 12 buds was found to occur on a single gonophore among the colonies examined. This material was collected on April 12, 1952.

The gastrozooids are arranged around the lips of sabellid tubes, sometimes forming a complete circle, the two tentacles and mouth facing the orifice of the tube. One colony, which was growing on a tube which was damaged on one edge, was located about 1.5 millimeters inside the lip of the tube. Because of the manner in which the lip of the damaged tube flared out, this placed the colony in direct contact with the bases of the worm's tentacles, which is the normal position, although its location inside the tube was unusual. The hydrorhizal net of this specimen started on the outside of the tube, traveled up the tube to its lip, and then down inside the tube to the ring of gastrozooids. The location of this colony suggests that the individuals may have migrated from the old lip to the new position, although it may be that the hydroid settled upon the tube after it had been damaged. It is not known how "Lar" responds as its host lengthens and enlarges its tube, if indeed the worm does so, after a colony has established itself upon it.

The individual gastrozooids are never more than 1 millimeter tall and are rather stout, being 0.2 to 0.3 millimeter thick. The nematocyst pad on the "head" is well developed and is devoid of pigment, as is the ectoderm in general. The endoderm is brown.

The gastrozooids are connected to one another via a network of anastomosing, naked hydrorhizae, these hydrorhizae not exceeding 0.1 millimeter in diameter.

Tentacleless gonozooids occur as scattered individuals arising from the hydrorhizal net. The gonozooids are about 1 millimeter tall and bear a capitate, mouthless tip which is studded with nematocysts. From 2 to 12 medusa buds are borne on each gonozooid. They arise at irregular intervals slightly above the mid-point. The medusa buds show four spots of brownish-red pigment which correspond to the developing first order tentacle bulbs and also a brownish pigment mass representing the developing stomach. Medusa buds were seen pulsating on several colonies, but none were released before the specimens were preserved.

The nematocysts of the hydroid were studied and found to be as follows:

Macrobasic euryteles	20—28×8—11μ
Large microbasic euryteles	12—24×4— 6μ
Small microbasic euryteles	5— 8×2— 3μ
Desmonemes	6— 9×3— 4μ

The tentacles seem to possess only the small microbasic euryteles, whereas the macrobasic euryteles and desmonemes occur only in the cap of the gastrozooid. The large microbasic euryteles occur on the body of the polyp as well as in the cap. The body of the polyp also has small microbasic euryteles. Figure 5*i–l* illustrates the above nematocysts.

THE HOSTS: This species (*P. occidentalis*) has been found on two species of sabellids, *Potamilla neglecta* and *Pseudopotamilla intermedia*. These worms were kindly identified by Dr. Olga Hartman of the Allan Hancock Foundation. Sabellids are not well represented in the intertidal region near La Jolla, and only a few small specimens of *Pseudopotamilla intermedia* have been collected. These did not have any "Lar" upon them. The material upon which the hydroid was found was taken from 40 to 50 feet of water, as mentioned earlier.

DISCUSSION

A group of organisms, such as is represented by the genus *Proboscidactyla*, presents a number of interesting problems to the biologist. One of these problems concerns the matter of symbiosis, more specifically commensalism in this instance, and a second concerns the special life history of this group with the unavoidable complications encountered where the two phases of the life history are adapted to, or are adapting to, very different environmental factors.

In the Hydrozoa the tentacles, with their associated nematocysts, represent the primary tools for protection and food gathering, and there are few hydrozoans which can be pointed to as possessing reduced numbers of tentacles. *Protohydra* and *Tetraplatia* are curious among the Hydrozoa, indeed among the Coelenterata, in that these free living animals possess no tentacles at all. On the other hand, among the symbiotic Hydrozoa a rather large group of hydroids exists which possesses reduced numbers of tentacles, and some have none. Such forms as *Hydrichthys*, *Icthyocodium*, and *Nudiclava* are tentacleless, whereas *Monobrachium* has but one and *Proboscidactyla* but two tentacles. The possibility exists that the tentacleless forms exhibit a true parasitism in which the hydroid uses the hosts' tissues for its food, as was claimed for *Hydrichthys* by Warren (1916). The exact manner in which *Monobrachium* is adapted to its bivalved host is not clear inasmuch as living specimens have not been studied, but for at least two of the 2-tentacle *Proboscidactyla* we have adequate descriptions of the living animal (Gosse, 1857; Hand and Hendrickson, 1950). From these descriptions we can see how well fitted these animals are for their special way of life, but they seem to have sacrificed certain usual hydroid traits and the versatility of substrate requirements of most hydroids for the limited substrate offered by certain sabellids. The known genera upon which these hydroids occur represent but a small number of those which appear to be available. Only *Potamilla*, *Pseudopotamilla*, and *Schizobranchia* have so far been reported as bearing *Proboscidactyla*. Studies concerning host choice and relationships among this group would appear to be worth pursuing.

In most respects the life history of *Proboscidactyla* differs but little from that presented in freshman biology as characteristic of the Hydrozoa. However, a life history such as this, with two well-developed, relatively long-lived phases, is rather unusual in the animal kingdom and presents certain difficulties to the student of the group. The hydroid phase is, in general, a sessile stage, adapted to its own environment, whereas the medusoid stage is pelagic and is adapted to a completely different mode of life. Most students of the Hydrozoa look upon the hydroid phase as a stage in development specialized for asexual propagation and upon the medusa as the adult, sexually reproducing stage of the life history. Because of this curious division of the life history, students of the Hydrozoa have developed two "schools," the one a group of specialists in hydroids, the other in hydromedusae. Therefore, we find today that in many instances there are two sets of nomenclature referrable to a given animal, and there is no immediate hope of reducing this gigantic taxonomic snarl to a satisfactory systematic treatment. The prime hope would seem to be the study of life histories in this group so that the medusae may be referred to their proper hydroids, and then gradually the two systems will become one.

In the nearly 100 years since Gosse (1857) described the first "Lar," only three additional species have been described. These three all occur along the Pacific coast of North America, with one of them ranging to Japan. The actual number of species which exist cannot be determined at this time, but the possibility that as many as a dozen occur is not improbable. Uchida and Okuda (1941) list four certain species of medusae of *Proboscidactyla* with a fifth, originally described by Uchida (1927) as *Misakia typica*, also included as a distinct species. The status of several of the ten species and varieties of *Proboscidactyla* and *Willia* of Mayer (1910) certainly remains in doubt, although the present study validates Fewkes' *Willia occidentalis* and adds a new species, *Proboscidactyla circumsabella*. Foerster (1923), in an excellent study of the hydromedusae of the west coast of North America and particularly of the Vancouver Island region, lists four species of *Proboscidactyla*. Of these, two are merely cited from the literature (*P. occidentalis* and *P. ornata* var. *stolonifera*), but the other two (*P. flavicirrata* and *P. polynema*) concern specimens taken in the Vancouver Island area. Foerster reported ocelli on the tentacle bulbs of *P. flavicirrata;* however, this statement and that of Uchida and Okuda (1941) are the only known instances where ocelli have been reported for proboscidactylans. In each instance, however, the report has concerned *P. flavicirrata*, so ocelli may occur in that species although specimens examined by the writer have not possessed ocelli. The species *Proboscidactyla polynema* of Foerster is referred to the animal described from the Atlantic by Hartlaub (1917) as *Pochella polynema*. This medusa has no cnidothylacies (centripetal canals of Foerster), and each primary radial canal gave off about six lateral branches on each side. These characters would make this an unusual species of *Proboscidactyla*, if, indeed, it is one at all.

The following four species of *Proboscidactyla* now have been described for both the hydroid and medusoid stage of the life history.

P. stellata (Forbes) (Hydroid *Lar sabellarum* Gosse)
P. flavicirrata Brandt
P. occidentalis (Fewkes)
P. circumsabella n. sp.

This leaves an ample number of hydroid stages to be described, such as the several which presumably live along the Atlantic coast of the United States. At least one of these hydroids is known to occur in Long Island Sound (E. S. Deevey, *in litt.*). This hydroid will probably be identified with the medusa *P. ornata* (McCrady) when a critical study is made.

In considering a group of species it is always interesting to see if a key to their evolution or the manner in which they are related can be found. A group such as *Proboscidactyla* has no fossil record to help us, and today they are widely distributed. At least four species occur in the Pacific and an equal number in the Atlantic. This does not immediately suggest a key to their evolution.

If the hydroid stages of *Proboscidactyla* are compared, certain relationships are suggested. *P. stellata* and *P. flavicirrata* both have gonophores borne close to or upon the gastrozooids, whereas neither of the other two species whose hydroids are known is so constructed. Also, *P. stellata* commonly produces six-rayed medusae, whereas *P. flavicirrata* may have four, five, six, or eight radial canals. This suggests a relationship between these two, as the other two species seldom if ever produce anything other than four-rayed medusae. The nematocysts of the polyp stages of *P. stellata* and *P. flavicirrata* also resemble each other very much, but they also closely resemble those of *P. circumsabella* and *P. occidentalis*.

The gonozooids of the four species do not give us much help beyond their location on the colony. In *P. stellata* four medusa buds are usually produced, whereas *P. flavicirrata* may have up to eight buds; *P. circumsabella* seems never to produce more than four, whereas *P. occidentalis* produces up to 12.

The adult medusae of *Proboscidactyla* seem to offer the best evidence to their paths of evolution. *P. stellata* and *P. flavicirrata* have already been mentioned as having six or a variable number of radial canals, respectively, and it should be mentioned that *P. mutabilis* of the South Atlantic is even more variable than these two species. Of the three species of the present report, the northern species (*P. flavicirrata*) is largest and has more tentacles than its two southern relatives.

The nematocysts of the medusae are known for only the three species reported herein. Of the three, *P. occidentalis* is the most distinctive in that three sizes of macrobasic euryteles are present of which one, the medium size, is very unusual in shape. *P. flavicirrata* and *P. circumsabella*, on the other hand, possess only two sizes of macrobasic euryteles. If the nematocysts of the medusae are used to indicate relationships, it appears that the latter two species are more closely related to each other than to *P. occidentalis*. In summary, then, it appears that *P. stellata* and *P. flavicirrata* are closely related, the latter being also near *P. circumsabella*. *P. occidentalis* is somewhat more distantly related to these others in both its morphology and its geographic location.

Another interesting medusa, *P. ornata* (McCrady) var. *stolonifera* Maas, has been reported from the Pacific at Acapulco harbor (Mexico) by Bigelow (1909) and from the Malay Archipelago by Maas (1905). This variety should be elevated to at least the rank of subspecies and will be so considered in this study. *P. ornata stolonifera* is a good-size medusa (about 5 mm. diameter) but has few tentacles as compared to other Pacific species, its maximum number being about 20. Also, it is distinctive from other Pacific species in its possession of medusa-bearing stolons. It appears that this subspecies has been derived from the Atlantic *P. ornata–P. ornata gemmifera* complex, *P. ornata* (McCrady) being known from southern New England to Beaufort, North Carolina, and *P. ornata* (McCrady) var. *gemmifera* Fewkes (see Mayer, 1910, for first usage of this combination) from North Carolina to the Bahamas. As in the instance of the variety *stolonifera*, this variety (*gemmifera*), will be considered a subspecies. The species *P. ornata* is distinguished from its subspecies, *P. ornata gemmifera*, by the habit of the latter of producing medusa-bearing stolons which arise from the radial corners of the stomach. Thus we have an interesting series of medusae, ranging from New England to the Bahamas, which, as southerly regions are reached, seem to develop the character of asexually producing medusae from the medusa stage, and this southern form has a close relative in the warm waters of the Pacific which has a similar characteristic. If one allows the speculation, it seems possible that the Pacific *P. ornata stolonifera* was separated from the Atlantic *P. ornata gemmifera* after a period of submergence and emergence of the Panamanian Isthmus. It would be of real interest to study the host substrates of the "*ornata* complex" to see if these worms are related in a manner similar to that of the medusae.

Kramp (1952) has reported *Proboscidactyla ornata* from the west coast of Chile. He had but a single 3-millimeter specimen at his disposal, and this specimen was not in good shape. The possibility that *P. ornata* exists along the coast of Chile will not be denied; however, it may well be that this particular specimen really represents a young specimen of *P. mutabilis* or an undescribed species. That Kramp's medusa was not a *P. ornata* seems even more likely if one considers the known distribution of this species and its subspecies in conjunction with the existing current systems (see, for example, Chart VII in Sverdrup, Johnson, and Fleming, 1946).

Uchida (1927) rather thoroughly surveyed the anthomedusan fauna of Japan and in this study listed five forms of what now make up part of the genus *Proboscidactyla*, but did not at that time recognize *P. flavicirrata* as occurring in that area. In a subsequent report Uchida and Okuda (1941) reported from Japan a hydroid and medusa they took to be that of *P. flavicirrata*, which I assume to be correct. The identification of *P. ornata* and *P. ornata gemmifera* in Japan (Uchida, 1927) presents a problem in distribution and systematics. The *P. ornata* may well be the young of *P. flavicirrata*, but the phenomenon of budding in the medusoid stage has not been reported for this latter species, so that there is no ready suggestion as to what this budding form may have been. That *P. ornata* and some of its subspecies do or do not occur in Japan cannot be stated with certainty at this time. Moreover, the answer to this riddle may lie in the fact that the ability of medusae of this group to reproduce asexually may be more widespread than is now realized. A number of possibilities as to the identity of Uchida's *P. ornata* and *P. ornata gemmifera* certainly exist. The species *Willia stellata*, *Willia pacifica*, and *Misakia typica* of Uchida (1927) would best seem to be considered as synonyms of *P. flavicirrata*, although the critical test of this statement must await a study of their nematocysts.

In the many records of the occurrence of *Proboscidactyla*, one notable fact is that these medusae are absent from the high seas. They occur instead in bays and along the coasts of most parts of the world. This distribution must certainly be the result of the dependence of the hydroid upon sabellids, which worms are most common in shallow water. A second curious phenomenon concerning the distribution of *Proboscidactyla* is the extremely wide range of the species, *P. ornata*. Kramp (1952) lists this species from the Pacific coast of Mexico, Japan, the tropical Pacific, the Malayan Archipelago, and from Madras, India, and, further, from the Atlantic coast of North America, the Bahamas, Brazil, and Fernando Po on the west coast of Africa. The other species have much more localized distributions. Maas (1905) has pointed out that the habit of budding practically puts *Proboscidactyla* in a class with holoplanktonic organisms. Actually, the habit of budding does not seem to be a character of the genus but rather of the subspecies of *P. ornata* which, indeed, may well account for its curious and widespread distribution.

At this time it would appear that the following species exist, occupying in general the following areas. Most of the literature relevant to these distributions has already been cited, and that which has been omitted can be found in Mayer (1910) or Browne and Kramp (1939).

1. *P. flavicirrata*	North Pacific
2. *P. circumsabella*	Central Californian Pacific
3. *P. occidentalis*	Southern Californian Pacific
4. *P. stellata*	European North Atlantic
5. *P. ornata ornata*	Atlantic, New England to North Carolina
6. *P. ornata gemmifera*	East and West Tropical Atlantic
7. *P. ornata stolonifera*	East and West Tropical Pacific to Indian Ocean
8. *P. mutabilis*	South Atlantic and Straits of Magellan

The above species may be related and may have evolved along the following lines, but, of course, this is speculative. To begin with, I suggest a northern, inherently variable medusa such as *P. flavicirrata* which possibly as a circumpolar species gave rise to the Atlantic *P. stellata*. *P. flavicirrata* or its predecessor also gave rise to *P. circumsabella* and to *P. ornata*. *P. ornata* seems to have developed its southern subspecies *gemmifera* in the Atlantic which by spanning the Panamanian Isthmus has given rise to the subspecies *stolonifera* which has spread via the tropical current systems throughout the tropical Pacific. *P. occidentalis* may be the offshoot of *P. ornata stolonifera* or of *P. circumsabella* or some other species. The origin of *P. mutabilis* of the Falkland Islands and perhaps of the Pacific is not apparent. However, another pattern of evolution can be suggested which, based upon major existing ocean currents, seems even more plausible. Thus, starting with the variable *P. mutabilis* and utilizing the currents of the South Atlantic Ocean, medusae could be carried to the Isthmus of Panama, to the Gulf Stream, and into the North Atlantic to England. The Pacific species could be derived from a crossing at Panama or by moving directly into the Pacific from the circumpolar Antarctic currents. It would be possible to start at almost any point in the oceans and arrive at the same end results.

It is, of course, not necessary to accept any point or species as the origin of this group of medusae; the important fact would seem to be that today *Proboscidactyla* is a genus which occurs in most oceans and presumably has spread to these oceans via ocean currents acting upon the planktonic medusoid phase of its life history. One factor which would appear to limit the distribution of this genus in its spread would be a lack of suitable hosts. Therefore, if this group and its evolution are to be understood adequately, further studies are needed not only on the hydroids and medusae but also on the sabellids to whose fate *Proboscidactyla* has apparently attached its own hopes for the future.

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DEEP-SEA CHANNELS AND DELTA OF THE MONTEREY SUBMARINE CANYON

BY ROBERT F. DILL, ROBERT S. DIETZ, AND HARRIS STEWART

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Short Notes

DEEP-SEA CHANNELS AND DELTA OF THE MONTEREY SUBMARINE CANYON

BY ROBERT F. DILL, ROBERT S. DIETZ, AND HARRIS STEWART

Sonic and spot soundings by the U. S. Coast and Geodetic Survey and subsequent ontouring of these data by Shepard and Emery (1941) and the U. S. Coast and Geoletic Survey (Charts 5302 and 5402) show hat the continental terrace off Monterey Bay, California, is incised by one of the world's argest submarine canyons, known as the Monterey Submarine Canyon. However, beause of the sparseness of soundings at the ase of the continental slope, the nature of the egion around the canyon mouth remained ractically unknown until recently.

That the Monterey Canyon might have a hannel extending out over the deep-sea floor ike that of the Hudson Canyon (Heezen Ewing, and Ericson, 1951) was first suspected n 1949 when the fathogram from a cruise to he Arctic showed a small notch in the deepea floor many miles seaward of the Monterey roper. More recently, in connection with OFAR operations in the Monterey area, wo more crossings of this deep-sea channellike eature were made. Then, in December 1951, everal sounding lines were run with the Navy Electronics Laboratory vessel, the EPCE(R) 57—a 180-foot converted escort patrol craft quipped with an NMC-2 echo sounder. This urvey furnished sufficient data to establish he presence of a deep-sea extension of Monerey Canyon. A deltalike sedimentary apron xtending out from the mouth of the canyon as also revealed. The survey showed that he channels on the apron were in places ordered by leveelike banks. Two short cores ere taken—one in the axis of the channel and he other from a "natural levee."

Plate 1 was made from the recently obtained fathograms plus soundings from the United States Coast and Geodetic Survey. The contours of the shelf down to 1700 fathoms are well established by numerous soundings so they were taken directly from the U. S. Coast and Geodetic Survey Chart 5402 (contour interval 100 fathoms). Comparatively few soundings previously were available from the deep-sea floor so it is not surprising that the interpretation as shown in Plate 1 is quite different from that shown on chart 5402 and on the Shepard and Emery (1941) chart. This new interpretation shows a smooth deltalike fan extending out from the base of the continental slope. Two large channels and possibly a smaller one cut into this delta. The delta cannot be identified below the 2100-fathom contour. If this is the limit of the depth, the delta is about 60 miles long and 60 miles wide at its maximum cross section. It extends southwest from the mouth of the Monterey Canyon with a regional gradient of 60 feet per mile. If the delta has built up from a base level of 2100 fathoms, it has a total volume of about 26 cubic miles of sediment. By comparison the volume of Monterey Canyon is about 53 cubic miles.

The Monterey Canyon proper extends seaward for 50 miles from near the shore line in Monterey Bay to the base of the continental slope at 1700 fathoms. The topography of the canyon has been described in considerable detail by Shepard and Emery (1941, p. 72–78), Woodford (1951), and Crowell (1952, p. 75). In the 20 miles between the 1700- and 1800-fathom contours the canyon has a shallow U-shaped cross section. The gradient of the axis is low (30 feet per mile), so that the can-

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yon appears to lose its identity as a valley form. However, a short distance beyond the 1800-fathom contour, a channel again notches the deep-sea floor. In the vicinity of the 1850-fathom contour, two "distributary" channels break away from the main channel. All three channels assume courses roughly down the regional gradient of the delta. The west or main channel has a maximum width of 2.8 miles and a maximum depth of 750 feet. Its length is unknown, but it has been traced for 40 miles. A leveelike ridge with a relief of 90 feet is present on the outside of the west channel where it turns south. The central channel has a maximum width of 1.2 miles, a maximum depth of 480 feet, and an established length of 20 miles. However, where traverses were made, it has no leveelike ridges. It is also slightly shallower than the west channel. The east channel is small; its presence is based on only one crossing, so its extent is unknown.

Two short cores were obtained with a small gravity corer. The core 47 cm in length was taken from the axis of the main channel; the other, obtained from the leveelike ridge of the main channel, was 43 cm long. The core from the channel showed stratification and consisted of alternating layers of very fine-grained sand and a green micaceous terrigenous mud. The boundaries between the layers were sharp, but there was no evidence of graded bedding within the layers. The sand layers in this channel core were composed predominantly of a well-sorted quartz sand and ranged in thickness from 0.25 to 0.50 inch. The majority of the individual grains were angular to subangular with no evidence of frosting or other surface markings. The heavy-mineral suite indicates derivation from metamorphic and volcanic rocks of continental origin (E. L. Hamilton, Personal communication). The absence of any Foraminifera in the sand layers made it impossible to determine whether the sands had been transported from shallower water. However, this lack of Foraminifera does indicate rapid deposition.

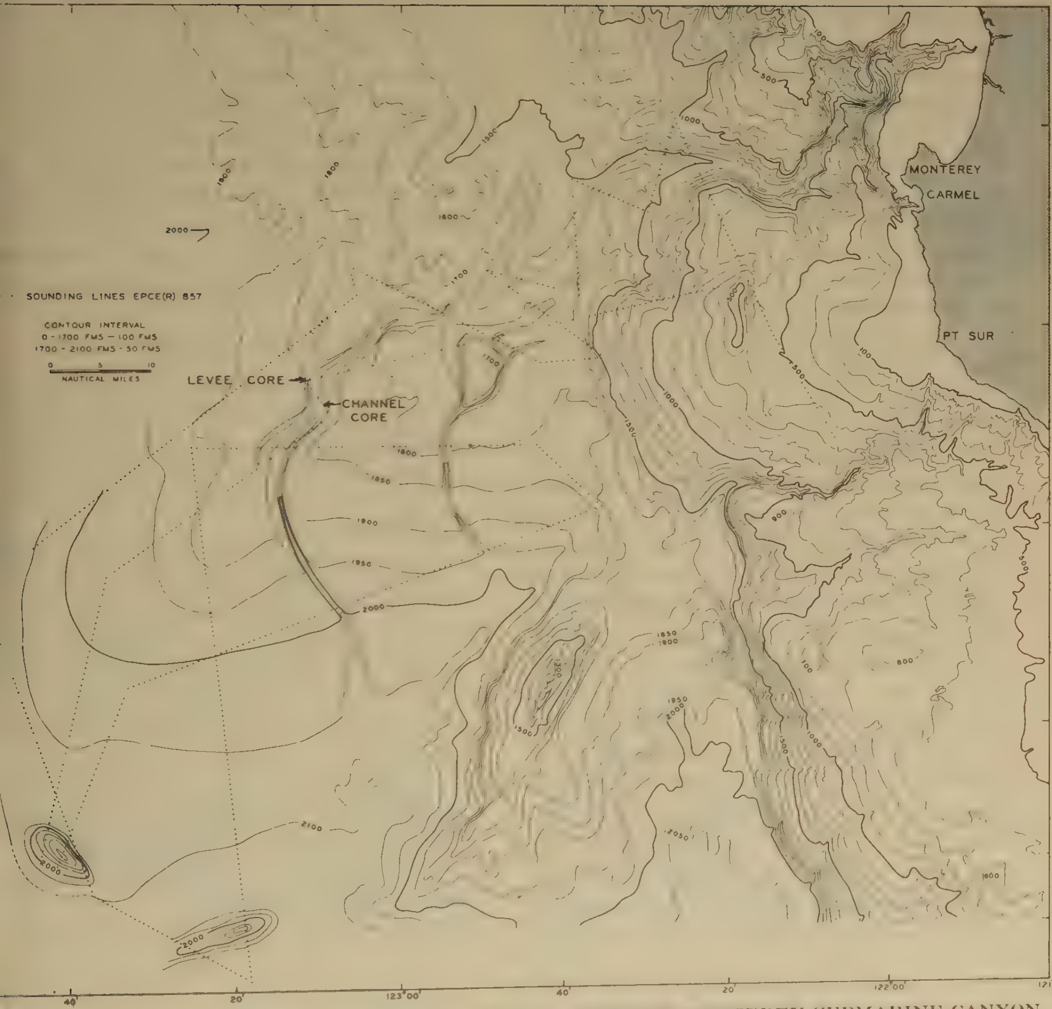
The fine-grained material between the sand layers consisted of homogeneous green terrigenous mud in layers 0.25 to 7 inches thick. The only material larger than silt size in these mud layers was mica and a few grains of presumed glauconite. The mud layers contain abundant Foraminifera. According to O. L. Bandy (Personal communication) the fauna is dominated by *Uvigerina senticosa*—a deep-water species typical of depths between 8000 to 12,000 feet (1300–2000 fathoms). No forms typical of shallow water were found.

The core taken from the levee bank consisted of homogeneous green micaceous terrigenous mud. This material is strikingly similar to the mud layers of the other core. Markings made by burrowing animals were present throughout the core.

The writers believe that subaerial processes did not form the delta and the channels at the base of the Monterey Canyon because: (1) a relative change of sea level of approximately 2 miles seems improbable, (2) deep-sea channels formed subaerially would probably have been destroyed in the passage of the strand line across them during a relative change in sea level of 2 miles, (3) the channels are well adjusted to the present slope of the sea floor; this would be unlikely if the channels are ancient subaerial channels that have been tectonically downdropped.

The processes that form submarine deltas can best be interpreted by the study of the surface features of this delta. One of the most important features is the leveed channels that meander across the broad submarine delta-fan much as do the subaerial leveed channels of a river. The similarity between the subaerial delta distributaries and the deep-sea channels is so striking that probably they are formed by similar processes. Since both subaerial and sublacustrine sediment-charged currents can form channels with leveed banks, it is reasonable to assume that deep-sea leveed channels are caused by sediment-charged currents. Menard and Ludwick (1951) have suggested that turbidity currents might produce leveed submarine channels. Although their existence on the sea floor has never been definitely demonstrated, such currents appear to offer the most logical explanation for these deep-sea channels.

The characteristics of the sediment collected neither strongly confirm nor deny the turbidity-currents hypothesis. The two short cores certainly are not an adequate sampling of the


MONTEREY
CARMEL
PT SUR
LEVEE CORE
CHANNEL CORE
· · SOUNDING LINES EPCE(R) 857
CONTOUR INTERVAL
0 - 1700 FMS — 100 FMS
1700 - 2100 FMS - 50 FMS
0 5 10
NAUTICAL MILES
100
500
1000
1500
1600
1700
1800
1850
1900
1950
2000
2050
2100
800
900
40'
20'
123°00'
40'
20'
122°00'
121°40'

SHOWING THE DEEP-SEA CHANNELS AND DELTA OFF THE MONTEREY SUBMARINE CANYON
that soundings less than 1800 fathoms are contoured with a 100-fathom interval and those deeper than 1800 fathoms with a m interval. The new sounding lines, on which this interpretation of the topography off the Monterey canyon is based, are by the lines of dots. The other contours outside this area are taken from the U. S. Coast and Geodetic Survey chart 5402 or hepard and Emery (1941).

environment. However, in conformity with the principle of isostasy, the bedrock in the abyssal sea-floor region of the channels is presumably dense basic rock. If so, the acidic mineral assemblage shows that this sediment was derived from the continental block. Although the writers believe that much of this sediment was probably carried out by turbidity currents, other processes can also account for this mineral assemblage. The presence of fine sand layers in the core from the channel and their absence in the core from the levee suggests that the currents which deposited the sand layer may also have formed the channels. Inasmuch as only two cores were collected, the presence of sand layers in one core and not in the other may be purely fortuitous. The sand layers also indicate some type of bottom current, and the absence of an indigenous Foraminifera fauna in this sand suggests a rapid emplacement of these sand layers.

The delta and the deep-sea channels may have developed as follows: Sedimentation causes oversteepening and eventual slumping of sediment in Monterey Canyon, which initiates a turbidity current. Because of the steep gradient, these currents accelerate as they flow down the axis of the canyon, probably increasing in size by picking up sediment. Once a flow reaches the deep-sea floor the low gradient of the bottom reduces the velocity, so that the flow becomes predominantly depositional. In this way a wedge of sediments is built up to form an undersea alluvial fan the surface of which is a plane of equilibrium. The fan slowly fills the mouth of the original V-shaped canyon as it laps up on the continental slope. As successive flows leave the canyon mouth, friction against its moving front and lateral mixing with the surrounding water cause a decrease in the velocity at the edges of the flow resulting in deposition along the sides. Subsequent flows tend to be channeled between these lateral deposits or levees, building them up and extending them seaward. Thus the channels are developed by a process of erosion and differential deposition along a profile of equilibrium. The number of channels and the shape of the delta proper indicate that these channels may meander across the surface as do the channels of land deltas, spilling their sediments first in one area and then in another so that the end result is a large fan-shaped delta similar to those found on the continents.

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OBSERVATIONS ON THE SEXUAL BEHAVIOR AND SPAWNING OF THE SQUID, *LOLIGO OPALESCENS*, AT LA JOLLA, CALIFORNIA[1]

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INTRODUCTION

It has long been known that the Pacific Coast squid, *Loligo opalescens* Berry, tends to migrate to certain inshore areas for spawning. This same habit has been described for certain other species of the genus, *L. pealii* of the Atlantic Coast of North America (Verrill, 1881) and *L. vulgaris* in Northern Europe (Tinbergen and Verwey, 1945). This inshore migration generally occurs in the late spring and summer months in the two Atlantic species. But, according to Fields (1950) the egg masses of *L. opalescens* may be found at Monterey Bay, California, during any month of the year, but the most intense spawning is during April, May, June and July, with a minor peak occurring in November. As a result of the availability of specimens near shore during the spawning period, many studies have been made on the embryology of the genus, and Drew (1911) observed copulation and spawning in the aquarium. However, no one appears to have observed these activities in nature.

An unusually large spawning population of *L. opalescens* appeared in the La Jolla area during February and March, 1953. This provided the author with an opportunity to make direct observations in the field and thus to corroborate and supplement the observations of Drew, Tinbergen, Fields and others.

ACKNOWLEDGMENTS

I wish to thank Mr. Ivan Simpson of the U. S. Navy Electronics Laboratory who was my diving companion during this investigation. Special thanks are due to Mr. Conrad Limbaugh of Scripps Institution of Oceanography, whose instruction in the use of, and whose loan of diving equipment made this investigation possible. I also wish to thank Dr. Martin W. Johnson of Scripps Institution for valuable criticisms and suggestions. Mr. Donald Lear and Mr. Sam Hinton, both of Scripps Institution, also provided me with much valuable assistance.

FIELD AND LABORATORY OBSERVATIONS

On February 16, 1953, a local fisherman reported that the net he had set two days earlier was so heavily laden with squid eggs that he could

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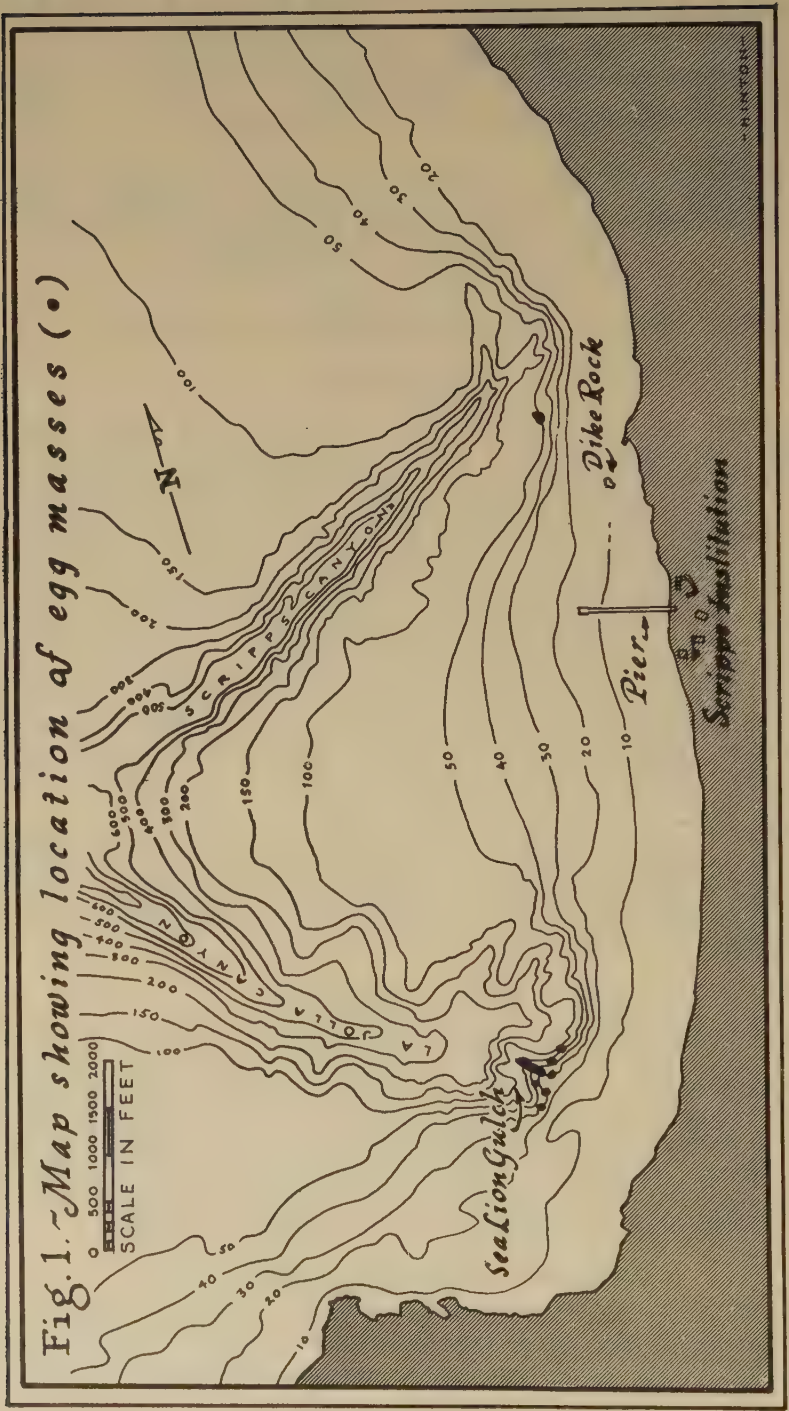
SCRIPPS CANYON
LA JOLLA CANYON
Dike Rock
Pier
Scripps Institution
Sea Lion Gulch
N
SCALE IN FEET
0 500 1000 1500 2000
10
20
30
40
50
100
150
200
300
400
500
600
HINTON

Fig. 1.—Map showing location of egg masses (•)

FIGURE 1

not raise it out of the water. Through interviews with this and other fishermen, it was learned that large schools of squid had been in the vicinity of the La Jolla submarine canyon about 1,400 feet offshore for a period of about a week. At about this time Aqua-lung divers from Scripps Institution of Oceanography reported large numbers of dead squid lying on the bottom at depth of from 30 to 70 feet. As a result of these reports, a special investigation was made. The methods employed were: (1) diving with the use of an Aqua-lung at various points in the area to explore for the site of the chief spawning areas and to recover eggs; (2) plankton hauls for squid larvae at the surface and near the bottom to determine when hatching took place and how long the larvae remained in the vicinity; (3) rearing of the freshly laid eggs, in the laboratory, to determine the length of time required for the embryos to reach the hatching stage and to obtain freshly hatched larvae to aid in identifying those caught in the plankton.

RESULTS

Diving Observations

The first of a series of dives was made by the author and a companion on March 8, 1953, in the vicinity of the Scripps submarine canyon (Figure 1) at a depth of 50 feet. The bottom of this area is sandy with occasional small rocky outcroppings. The water temperature at this time was 12.6 degrees C. Observations on the bottom indicated that a mass mortality of the adult squid population was taking place; the bottom was littered with dead and dying squid. The estimated concentration of squid was one to two individuals per square foot and this situation held for the entire distance that we were able to survey (75-100 yds.). A large mass of egg capsules was discovered attached to the sandy bottom along the general trend of the 50-foot contour. This mass was estimated to be 10-15 feet in diameter. There were great numbers of actively swimming squid in the immediate vicinity of the mass. Many females were seen depositing their individual egg capsules around the periphery of this mass. The manner in which they deposited their eggs and their activities at this time were similar to those of *Loligo pealii* as described by Drew (1911), except that the egg capsules were never attached to protruding objects such as shells or rocks but always to the base of some previously laid egg capsule. A short distance above the egg mass a number of copulating pairs of squid were seen.

Of the two methods of copulation described by Drew (1911) for *L. pealii* only one was observed in *L. opalescens*. In this method the male is ventral to the female and has his arms and tentacles wrapped around her mantle just posterior to her mantle opening. While in this position the male is able, with his left ventral arm, to grasp the packet of spermatophores as they are extruded from his siphon and insert them into the mantle cavity of the female (Figures 2 and 5). Since all of the pairs in the vicinity of the egg mass were in this position, it appears that this method is employed just previous to egg-laying. However, sperm were also found in the buccal sperm receptacles of the females (Figure 4) and this would indicate that the second method of

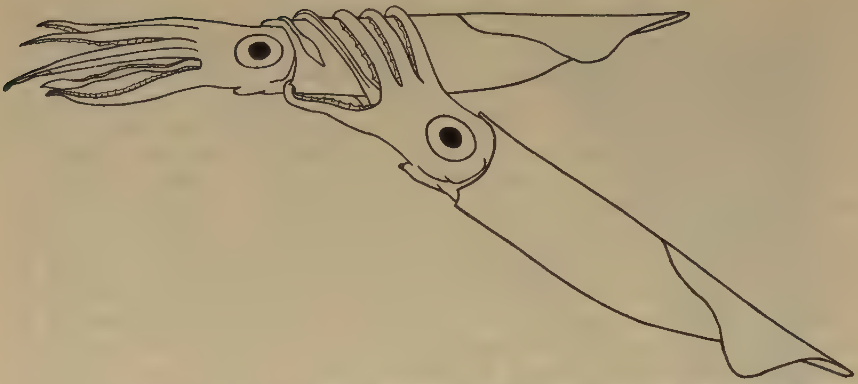

FIGURE 2. Semidiagrammatic illustration of copulating squid showing the animals' position when spermatophores are transferred to the mantle cavity. Drawn from observations in life. Male is embracing female from below.

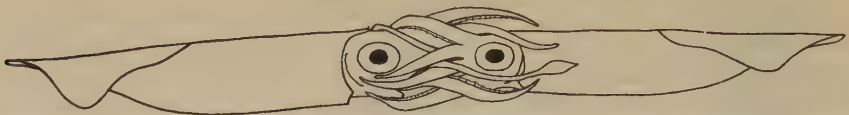

FIGURE 3. Semidiagrammatic illustration of copulating squid showing the animals' position when spermatophores are transferred to the buccal sperm receptacle. After Drew.

copulation described by Drew (Figure 3) is also used. But since this second method was never observed during any of the dives, it seems likely that the squid use it at some time previous to their arrival on the spawning grounds. A collection of living and dead squid was made at this time.

The next day, March 9th, another dive was made at the head of the La Jolla submarine canyon (Figure 1). The water temperature at this time was 12.4 degrees C. During this dive, large schools of squid were seen in the waters immediately above the canyon. As many as a dozen large egg masses were seen, one was estimated to be at least 40 feet in diameter. These masses seemed concentrated along the edges of the canyon, some of them being on the more gentle slopes and shelves of the canyon wall itself. One such mass, situated on a fairly steep slope, was followed from a depth of about 70 feet down to a depth of 114 feet and appeared to continue on down even farther. At some places in the vicinity of the 40-foot contour, the sandy bottom was completely covered with dead squid. The activities of the squid observed at this time were the same as those seen the previous day near Scripps canyon. A number of squid and freshly-laid eggs were collected. The eggs were promptly placed in an aquarium of running sea water and kept for further study.

The living animals observed on this dive were all very pale and there were large shreds of epithelium hanging down from their mantles. Those collected had a loose flaccid consistency of the body unlike the firmness characteristic of squid caught in open waters during other seasons of the year. This ''spent'' condition of the population is, according to Fields (1950), a result of spawning and occurs occasionally at Monterey Bay during June and September.

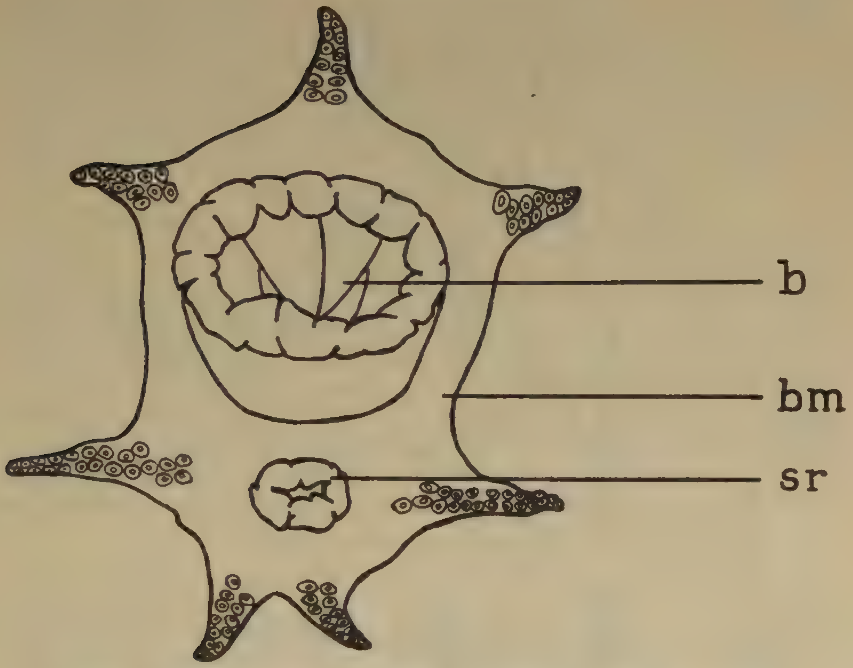

FIGURE 4. Semidiagrammatic illustration of the buccal membrane of the female. (b) beak, (bm) buccal membrane, (sr) sperm receptacle.

During this and the following six weeks, other divers from Scripps Institution, who were engaged in geological research in other parts of the La Jolla Bay region, reported only occasional small groups of egg masses which had become detached from the substrate and were merely lying on the bottom.

As soon as it was apparent that the canyons and their environs were the chief areas of spawning in the bay, all subsequent dives and plankton hauls were made there. Since it was impossible to make routine surveys of both canyon spawning areas, it was decided to follow one relatively small spot where the spawning seemed to be most intense. The area selected was that branch of the La Jolla submarine canyon known as Sea Lion Gulch. Dives and bottom and surface plankton hauls were made every third day during the second and third weeks in March. After this, only weekly dives and plankton hauls were made for the next five weeks, weather permitting.

Laboratory Observations on Animals Collected by Diving

Measurements made on random samples of dead and dying adult squid taken from the bottom gave a modal size of from 15-16 cm. mantle length for the males and from 14-15 cm. mantle length for the females. This is one centimeter smaller than the modal sizes for both males and females of the Monterey Bay spawning population of *L. opalescens* (Fields, 1950), and 5 cm. smaller than the males and 2 cm. smaller than the females of a spawning population of *L. vulgaris* at Helder, Netherlands (Tinbergen and Verwey, 1945). The sex ratio obtained from this

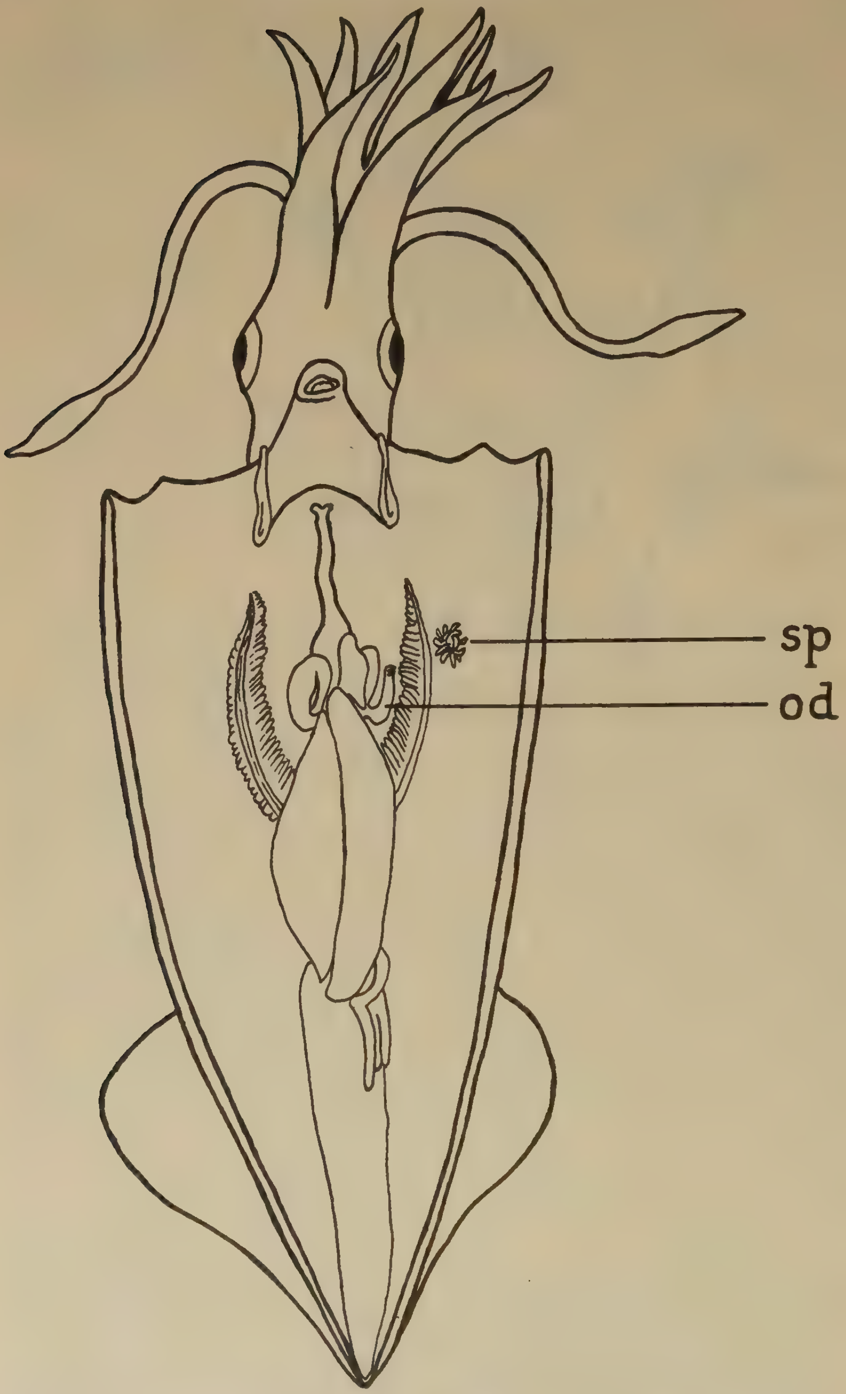

FIGURE 5. Ventral view of female with mantle laid open to show place of attachment of spermatophores under mantle. (sp) spermatophores, (od) oviduct.

sampling was unequal, the males comprising 63 percent of the population. According to Tinbergen and Verwey (1945) the sex ratio of their spawning population was unequal, 57 percent being males.

An examination of the guts of the females showed them to be completely empty. The guts of the males contained only a few shreds of mantle epidermis which had apparently been torn from the female.

Results of the Plankton Hauls

A 40 cm. Hansen type plankton net was used to make 10-minute hauls over the vicinity of Sea Lion Gulch. These hauls were made at the surface and as close to the bottom as possible, for a period of six weeks after the main spawning was observed. Only four larval squid were caught in these hauls, although diving observations made at the time the plankton hauls were taken indicated that the number of egg capsules in the vicinity was progressively decreasing. While it would have been more desirable to use a larger net and to cover a larger area of the bay, it is believed that the results of the plankton hauls taken are significant and that they indicate that the larval squid did not stay in the vicinity of the spawning grounds but were swept away by currents.

Result of Egg Rearing in the Laboratory

The freshly laid egg capsules which were brought into the laboratory were maintained in aquaria of running sea water at an average temperature of 13.6 degrees C. The egg capsules are from 3½ to 4 inches long when first laid but swell to 8 or 10 inches within a few days. Development to hatching stage required from 30 to 35 days. The freshly hatched larvae have an over-all length of 4.5 mm. and a mantle length of 2.5 mm. There was a 25 percent mortality of the eggs. This mortality, however, was apparently induced by laboratory conditions because the eggs in nature, observed by diving, showed no mortality, even up to the hatching stage. The larvae hatched in the laboratory still had a very small yolk sac. This sac persisted for about a day. No attempt was made to rear the larvae beyond this stage.

It was noticed that after about the second week the egg capsules which were kept in the laboratory were infected with a large, bright red polychete worm *Capitella ovincola* (identified by Dr. D. J. Reish). The egg capsules which were observed in nature at this time were also parasitized by *C. ovincola.* The worms did not appear to be feeding upon the developing embryos but merely to be boring through the gelatinous matrix of the egg capsule. As many as 15 of these worms were found in a single egg capsule. The egg capsule also provided a substrate for two other organisms, the hydroid *Obelia geniculata* (identified by Dr. Cadet Hand) and naviculoid diatom.

SUMMARY

The sequence of events in the spawning of *L. opalescens* as based on the above observations and on those of other authors seems to be as follows: (1) a population which is ready to spawn moves from offshore into a relatively shallow area near shore. It seems probable that at this time the males transfer sperm to the buccal seminal receptacles of the females. (2) The squid tend to congregate near the sandy bottoms of semiprotected bays. (3) A few minutes before the females lay their eggs the males transfer a second group of spermatophores to a place under the left side of the mantles of the females. (4) The females attach their egg capsules either to the sandy bottom or to the base of some previously laid egg capsule. This results in large masses of egg capsules, which may be as much as forty feet in diameter. (5) Both males and females die after spawning. (6) The eggs require from 30 to 35 days to hatch at a temperature of 13.6 degrees C.

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UNDERWATER MAPPING BY DIVING GEOLOGISTS

BY

H. W. MENARD, R. F. DILL, E. L. HAMILTON, D. G. MOORE,
GEO. SHUMWAY, M. SILVERMAN, AND H. B. STEWART

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VOL. 38, NO. 1 (JANUARY, 1954), PP. 129-147, 15 FIGS., 1 TABLE

UNDERWATER MAPPING BY DIVING GEOLOGISTS[1]

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ABSTRACT

Self-contained diving equipment makes it possible for properly trained geologists to map the continental shelf to a depth of 120 feet. The equipment opens about 1,000 square miles of the sea floor off southern California to inspection by geologists. Much of the area may contain enough outcrops to be mappable.

This new technique was used to map about 2 square miles of the continental shelf on the north side of San Nicolas Island, California. Two mapping teams each consisting of two divers and a recorder-navigator operated in small boats based on a ship. Two days were spent diving during a 4-day period. Outcrops were found at 26 of 28 stations and dips and strikes were measured at 25 stations. All stations were occupied by pairs of divers in accordance with standard safety procedure.

INTRODUCTION

Increasing interest in off-shore oil possibilities has provoked a corresponding interest in methods of mapping the geology of the sea floor. One possible method, indeed the most obvious one, is to put a field party on the sea floor. This method had not been tried in the spring of 1953 when the Navy Electronics Laboratory received a request from the Naval Ordnance Test Station, Inyokern, California, for information on the nature of the sea floor near San Nicolas Island. However, as most of the geologists in the Sea Floor Studies Section of NEL and many at the Scripps Institution of Oceanography are trained in the use of self-contained diving equipment (the aqualung), field mapping in shallow areas seemed feasible. This paper reports on the results of the underwater geological reconnaissance of two areas off San Nicolas Island and discusses the organization and usefulness of such surveys as a part of off-shore oil exploration. Detailed descriptions of self-contained diving equipment and other devices for underwater geology, and the procedure and limitations of free diving are included in the accompanying paper by Dill and Shumway.[4]

PRELIMINARY RECONNAISSANCE

Dill, Hamilton, and Menard made a reconnaissance at San Nicolas Island during the period, June 24–26, 1953, in order to determine if the sea floor was suitable

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[1] Manuscript received, October 30, 1953.
Navy Electronics Laboratory Professional Contribution No. 25.
Contribution from the Scripps Institution of Oceanography, New Series No. 671.

[2] Navy Electronics Laboratory, San Diego.

[3] Scripps Institution of Oceanography, La Jolla.

The writers are indebted to many people and organizations for cooperation and assistance in executing the geological survey off San Nicolas Island, in particular to: G. D. Burton and A. H. Staud of the Naval Ordnance Test Station, Inyokern; Mr. Van Dyke and Lt. Cavanah, U.S.N., of the Naval Air Missile Test Center, Pt. Mugu; Lt. R. E. Beattie, U.S.N., Officer in Charge of San Nicolas Island; Cdr. W. F. Malnate, Coast and Geodetic Survey; Utility Squadron 7, Pacific Fleet; and R. R. Revelle and F. P. Shepard of Scripps Institution of Oceanography. W. C. King, Jr., of Scripps gave valuable assistance as one of the four members of the diving teams.

[4] Robert F. Dill and George Shumway, "Geologic Use of Self-Contained Diving Apparatus," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 38, No. 1 (January, 1954), pp. 148–57.

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for geological mapping. Sea conditions which might affect small-boat operations and diving were studied from an AVR—a 63-foot air-sea rescue boat. Four reconnaissance dives were made at distances of $\frac{1}{4}$–$\frac{3}{4}$ mile from shore. Strike-ridges 3–10 feet high were found on three dives, and sand bottom was found on the fourth. The ridges were separated by narrow patches of sand a few inches thick. On the basis of this reconnaissance, a geological survey of the sea floor appeared feasible. The shore geology of the north side of San Nicolas Island was also studied and bench marks and suitable points for triangulation beacons were located as the concluding part of the reconnaissance.

GEOLOGICAL SURVEY

The survey party departed San Diego at 1600 on July 6, 1953, on board the "E. W. Scripps," a research vessel of the Scripps Institution of Oceanography, R. C. Newbegin, Master. The ship was anchored near the middle of area A-1 at 0700 on the following day. A shore party was dispatched to establish a triangulation network from bench marks on shore, and to determine the position of four dan buoys when they were planted. Simultaneously, a second party began to plant three dan buoys in an east-west line about $\frac{3}{4}$ mile from shore. When a boat returned after beaching the shore party, a third party began to lay one dan buoy and a line of small "diver" buoys at individual stations. The various buoys were planted before diving so that the positions of stations could be evenly spaced and and so that they could be located in minimum time during diving operations. Both sea parties began diving immediately after the buoys were planted (Fig. 2).

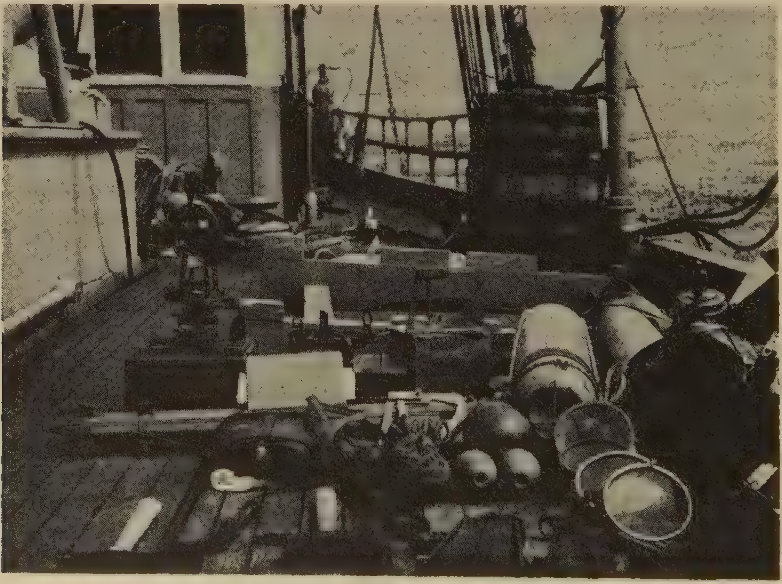


FIG. 1.—Representative equipment used during survey.

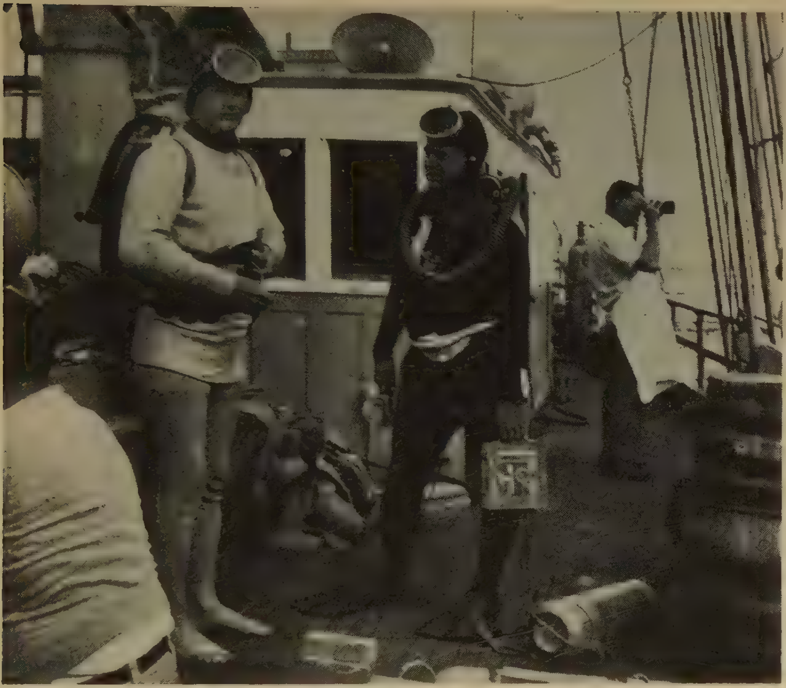


FIG. 2.—Geologists preparing for diving.

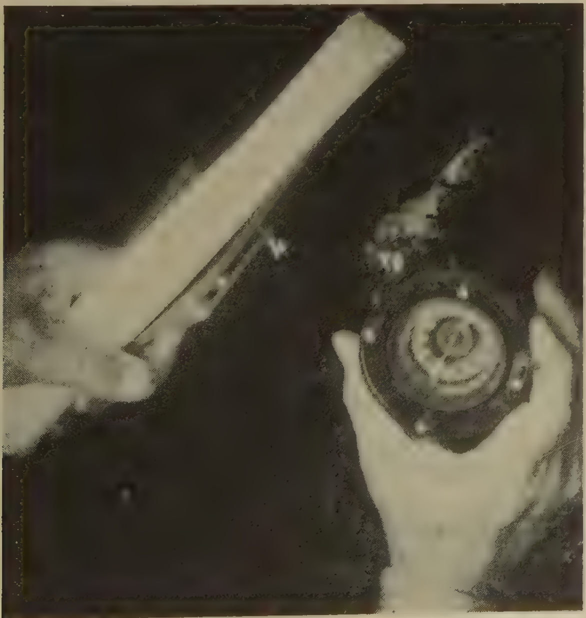


FIG. 3.—Determining strike of rock strata by aligning waterproof magnetic compass.

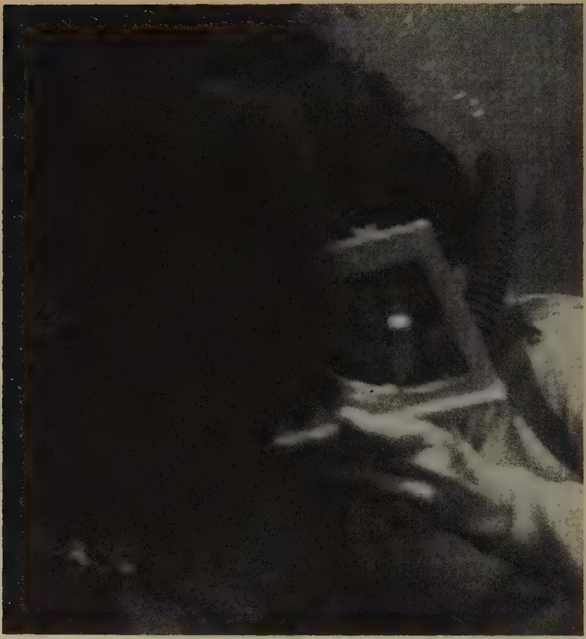


FIG. 4.—Measuring dip of rock strata by sighting along bedding plane in direction of strike.

FIG. 5.—Measuring dip by sighting down slope of bedding plane in direction perpendicular to strike. Note fish beside inclinometer.

FIG. 6.—Tying large rock sample on bottom for hoisting into boat.

The procedure on a typical station was as follows.

1. The approximate station location was determined relative to a preconceived network of stations. Stations were at buoys or at positions which could be determined while in a small boat by means of magnetic bearings, ranges, and predetermined horizontal sextant angles.

2. The boat was tied to a dan buoy if available. If not, it was tied to a convenient clump of kelp at the approximate position of the station. The kelp had the advantage of indicating the location of an outcrop.

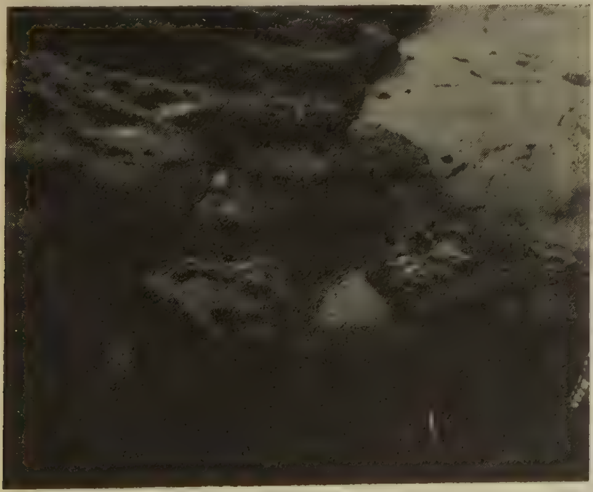
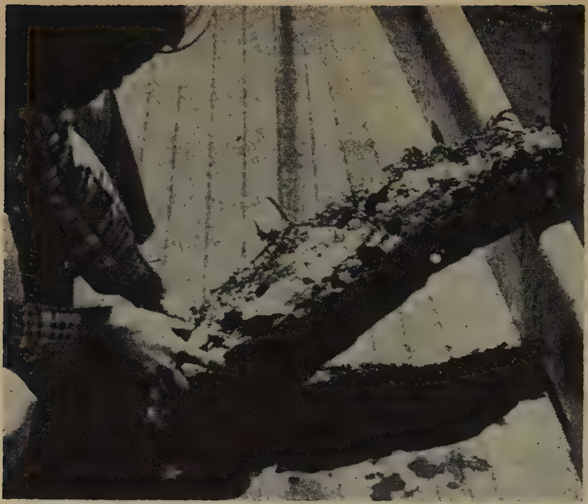


FIG. 7.—Outcrop of sandstone with some interbedded siltstone on beach adjacent to area A-1. Compare with Figure 15. Irregular outcrop of bedrock (in front of geologist) and surrounding smooth sand are typical of sea floor in areas A-1 and A-2.



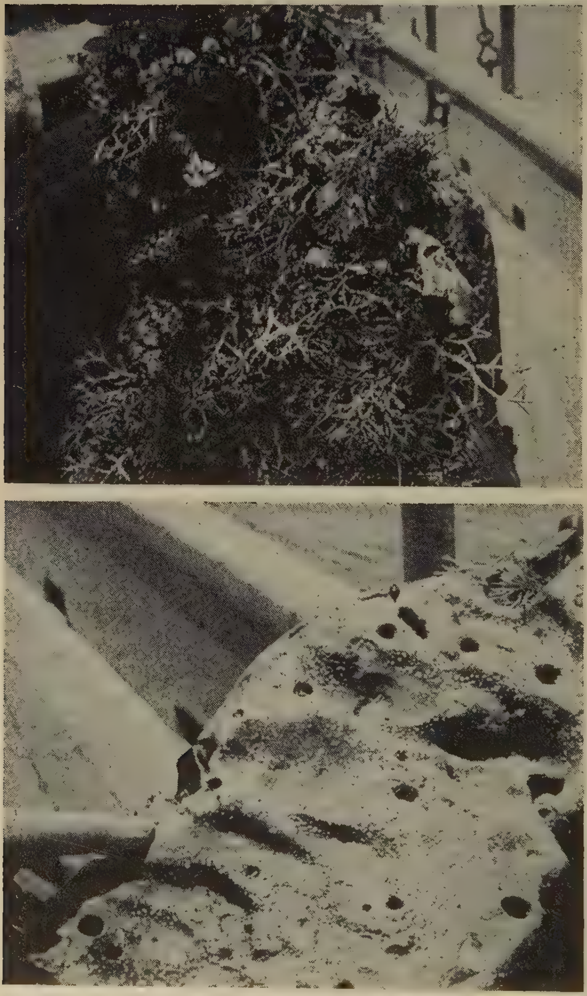


FIG. 8a.—Part of sandstone ledge showing importance of boring organisms in weathering of rock in shallow-water environments.

FIGS. 8b and 8c.—Close view of same sample showing difference in algal growth on top and bottom of ledge.

3. After the depth was determined by hand-line, two divers went down carrying a minimum of a geology pick, light sledge, magnetic compass, and inclinometer in a burlap bag. One diver collected a rock sample while the other determined the dip and strike of the bedrock (Figs. 3, 4, 5) and the extent and thickness of any patches of sand. Usually the second diver was then required to help collect the sample because of its large size. The divers returned to the surface with the sample or, if it was very heavy, they tied it to a line which had been lowered from the boat (Fig. 6).

4. Meanwhile, at the surface, the third man in the party took horizontal sextant angles on the dan buoys and on markers on shore in order to establish an accurate position. (The positions could not be plotted until the shore party completed its survey.) He noted the depth, prepared tags and bags for samples, and estimated and logged the position of the divers relative to the boat as indicated by the bubbles ascending from the aqualungs.

5. The divers reported on conditions of the bottom immediately upon climbing into the boat. All gear and samples were retrieved and the party moved on to the next station.

In this manner eleven stations were occupied on July 7 and five on July 8 (Fig. 9) before 1030, when operations were suspended. Buoys were retrieved and underwater photographs were taken during the afternoon of July 8.

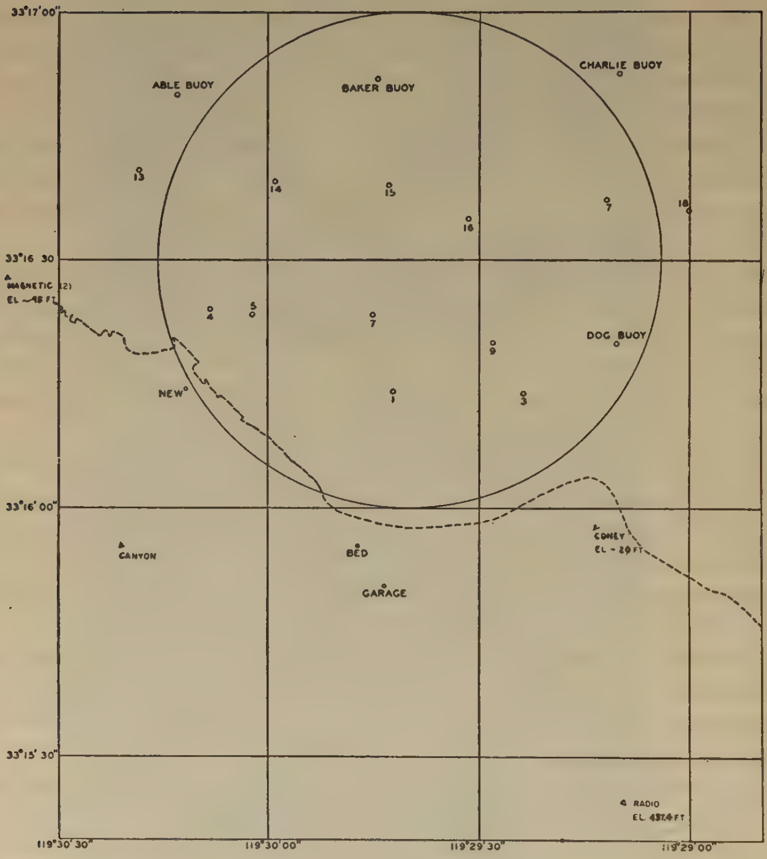
The ship was fog-bound in area A-1 until 1400, July 9, when it sailed for area A-2 and anchored in the area. A survey party was immediately placed on the beach, but diving was held in abeyance because of the difficulties of locating positions in patches of fog.

Area A-2 remained fog-bound until 1300, July 10, when diving operations began. No dan buoys were planted because of the likelihood that they would drift in this more exposed area. Each of the two parties returned to the ship after three dives and the stations were plotted while the divers rested. The approximate locations for subsequent stations were established and the parties began to dive again. Twelve stations were occupied during the day (Fig. 10); the last dive was completed at 2030, a few minutes after sunset.

The station under the ship was reoccupied on July 11 to check an apparently anomalous strike—which was verified. The ship sailed at 1000, and docked in San Diego on the morning of July 12.

GEOLOGY OF AREAS ON SEA FLOOR OFF SAN NICOLAS ISLAND

San Nicolas Island is composed of more than 2,000 feet of Eocene sandstone and shale intruded in a few places by Miocene(?) diabase dikes and covered extensively by Pleistocene terrace capping (Norris, 1951). The sandstones and shales have been folded and now form part of an anticline which plunges toward the southeast. The anticline has been deformed by two conjugate sets of normal faults trending approximately N. 10° W. and N. 70° E. The largest displacements known do not exceed 200 feet.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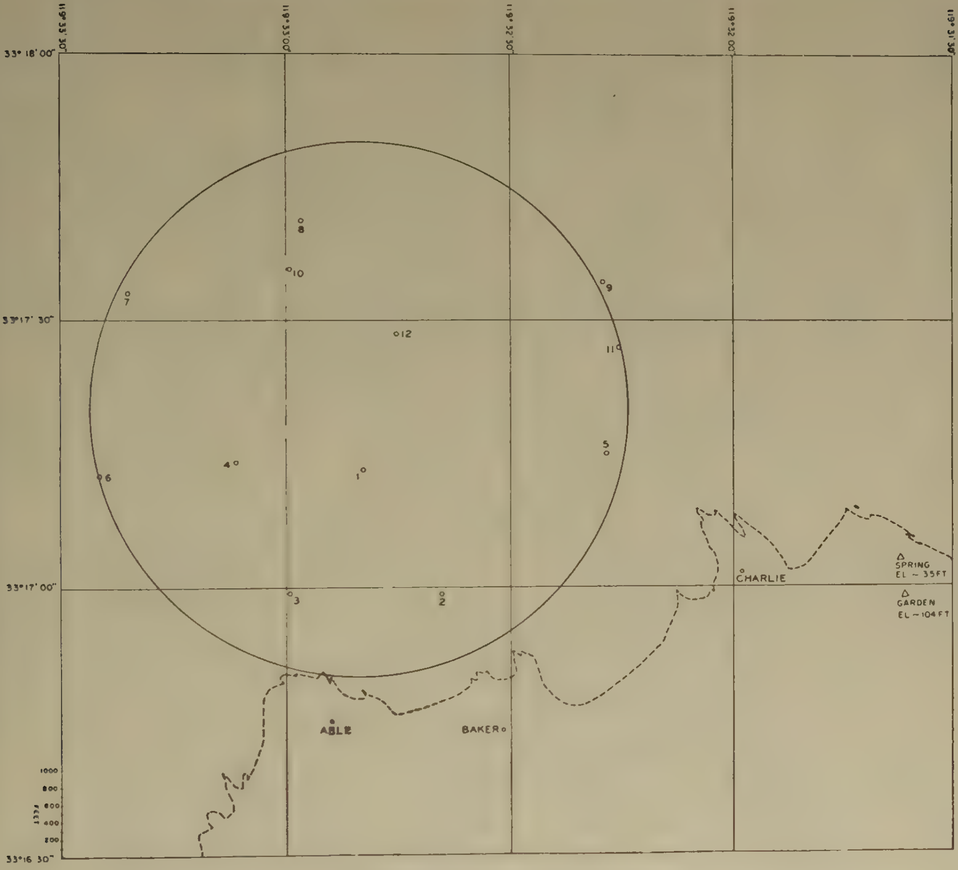
DOG BUOY
NEW
1
3
33°16'00"
CANYON
BED
GARAGE
CONEY
EL - 29 FT
33°15'30"
RADIO
EL 437.4 FT
119°30'30"
119°30'00"
119°29'30"
119°29'00"

FIG. 9.—Station locations in area A-1.

Structure.—The submerged areas studied in the present survey show no significant variation from the geology of the sub-aerial part of San Nicolas Island. The strikes in areas A-1 and A-2 are northwesterly and the dips are toward the northeast as would be expected from the position of the areas relative to the anticlinal axis (Fig. 11).

The minor variations in strike and dip within areas A-1 and A-2 may have resulted from minor crenulations on the anticlinal fold, but it appears more likely that they were caused by faulting. Norris (1951) has mapped several minor faults along the coast adjacent to area A-1. Most have a northerly strike so that they would be expected to extend across area A-1, but none has been traced at sea. However, other topographic trends, which probably mark faults, can be seen on vertical aerial photographs of area A-1. The photos, made especially for this survey by Utility Squadron 7 of the Pacific Fleet, were taken during a period of flat calm. As a result the water is completely transparent in most places and the bot-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8
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CHARLIE
SPRING EL ~ 35 FT
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ABLE
BAKER
1000
800
600
400
200
FEET

Fig. 10.—Station locations in area A-2.

tom can be seen in three dimensions to a depth of at least 70 feet. The submarine fault shown on the enclosed structural map is indicated on the photos by a narrow channel which transects the general trend of the bedrock. Minor normal faults striking north-south were found at the point where this probable fault reaches shore. The relative displacement on the minor faults is up on the east side which is the same as the relative displacement observed by Norris (1951) on the other faults in the immediate area. A series of resistant beds is truncated by the fault about ½ mile from shore and a similar series of beds appears at a different position on the opposite side of the fault. If the beds were continuous prior to the faulting, the relative displacement has been up on the east side. An additional indication of the displacement on this fault is given by the attitude of the rock at Station 9, which lies just east of the fault. The strike is more westerly than the strike at the surrounding stations. Drag along the fault surface would produce just such a change in trend if the relative movement was up on the east side.

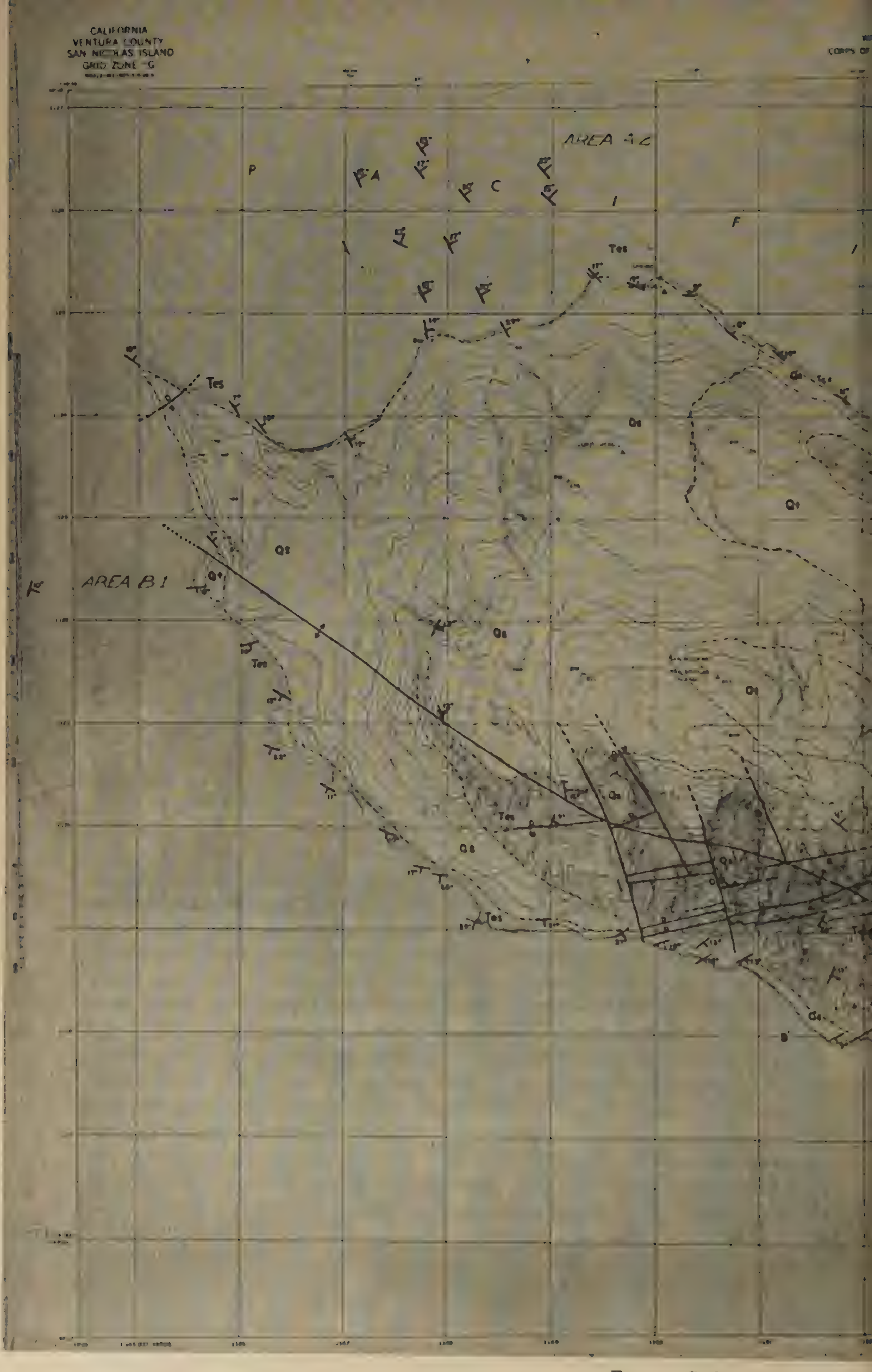
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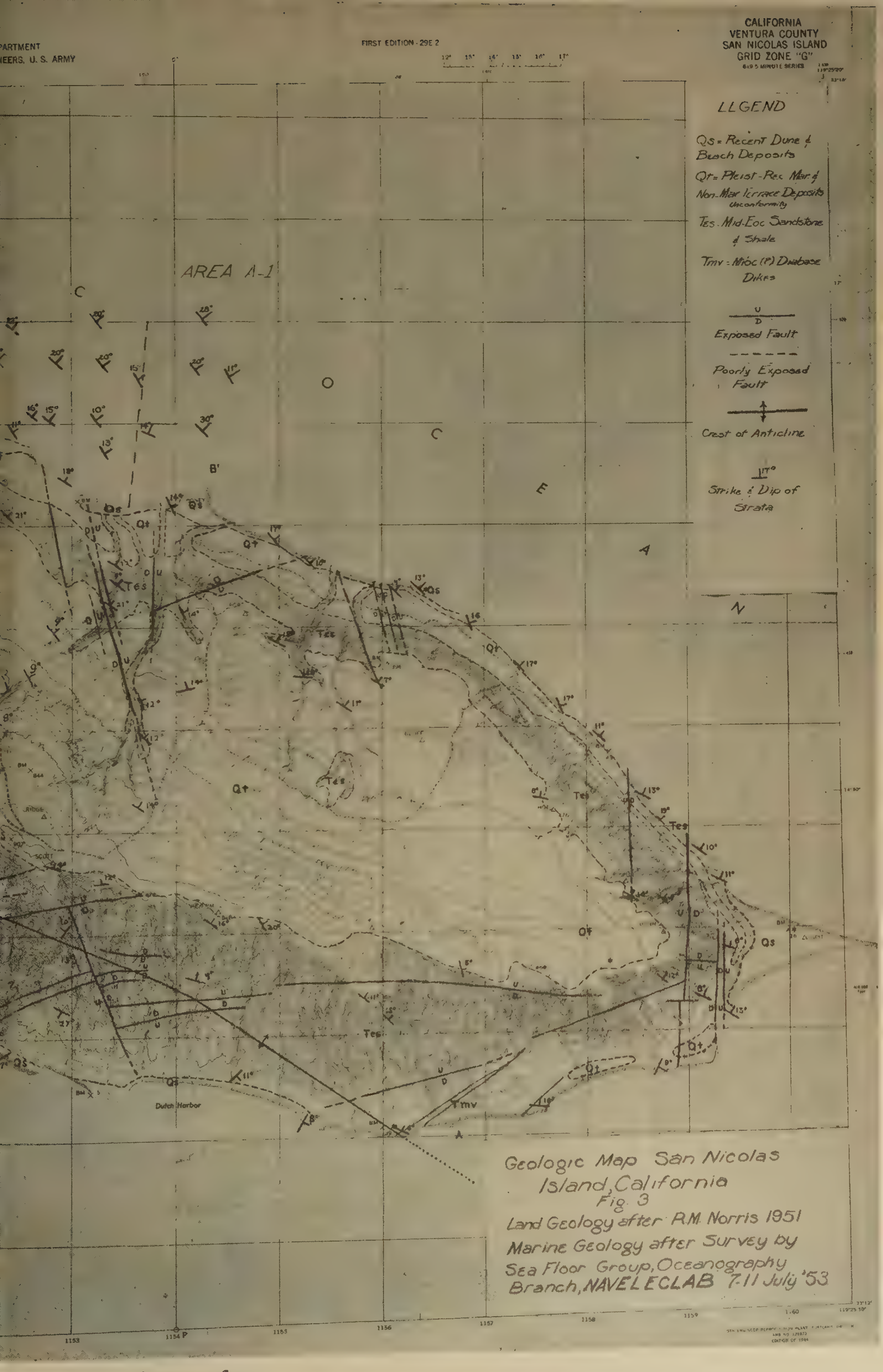
FIG. 11.—Geology of San Nicolas I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Qs = Recent Dune & Beach Deposits
Qt = Pleist-Rec Mar. & Non-Mar Terrace Deposits
Unconformity
Tes - Mid-Eoc Sandstone & Shale
Tmv = Mioc (?) Diabase Dikes
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Strike & Dip of Strata
AREA A-1
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Tes
Tmv
Dutch Harbor
A
Geologic Map San Nicolas Island, California
Fig. 3
Land Geology after R.M. Norris 1951
Marine Geology after Survey by Sea Floor Group, Oceanography Branch, NAVELECLAB 7-11 July '53
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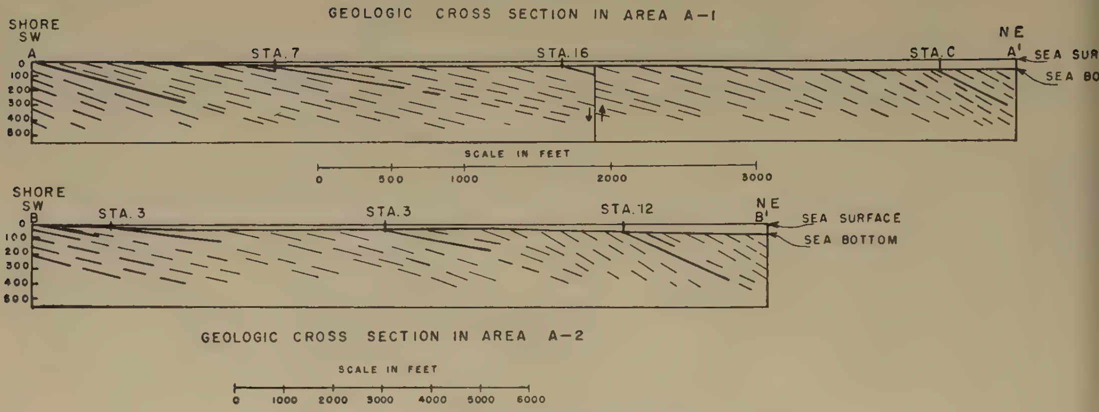
and and parts of adjacent sea floor.


GEOLOGIC CROSS SECTION IN AREA A-1
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STA. 12
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SEA BOTTOM
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100
200
300
400
500
GEOLOGIC CROSS SECTION IN AREA A-2
SCALE IN FEET
0 1000 2000 3000 4000 5000 6000

FIG. 12.—Geological cross sections of areas A-1 and A-2.

Lithology.—Sandstone was found at 14 of the 16 stations in area A-1, siltstone was found at one station, and bedrock was not found at one. In a general way the stations were randomly located relative to the type of bottom so it may be assumed that sandstone crops out almost everywhere. Some bias in favor of sampling resistant sandstones existed because it was impossible to obtain a large sample from the flat smooth troughs between ridges. Differential erosion which produced

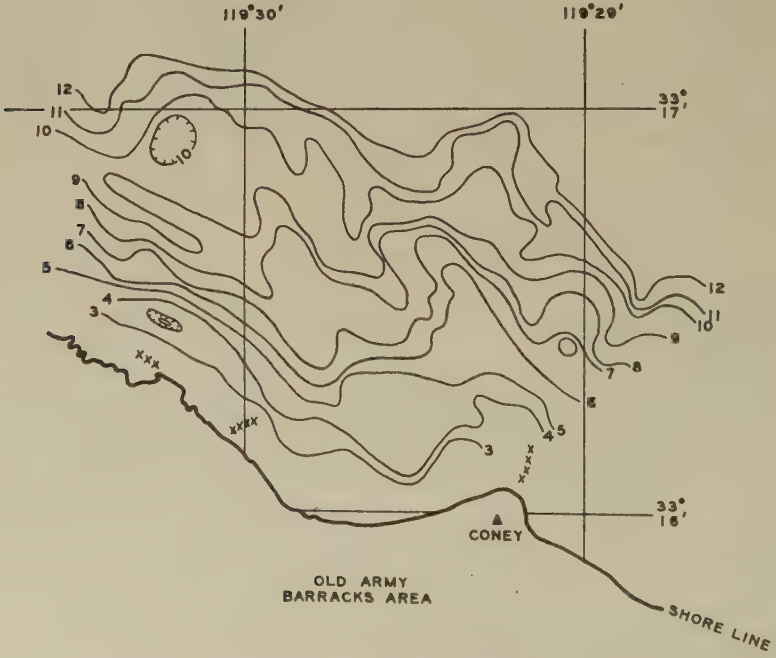
119°30'
119°29'
33° 17'
33° 16'
12
11
10
10
9
8
7
6
5
4
3
12
11
10
9
8
7
6
5
4
3
CONEY
OLD ARMY BARRACKS AREA
SHORE LINE

FIG. 13.—Bathymetry of area A-1.

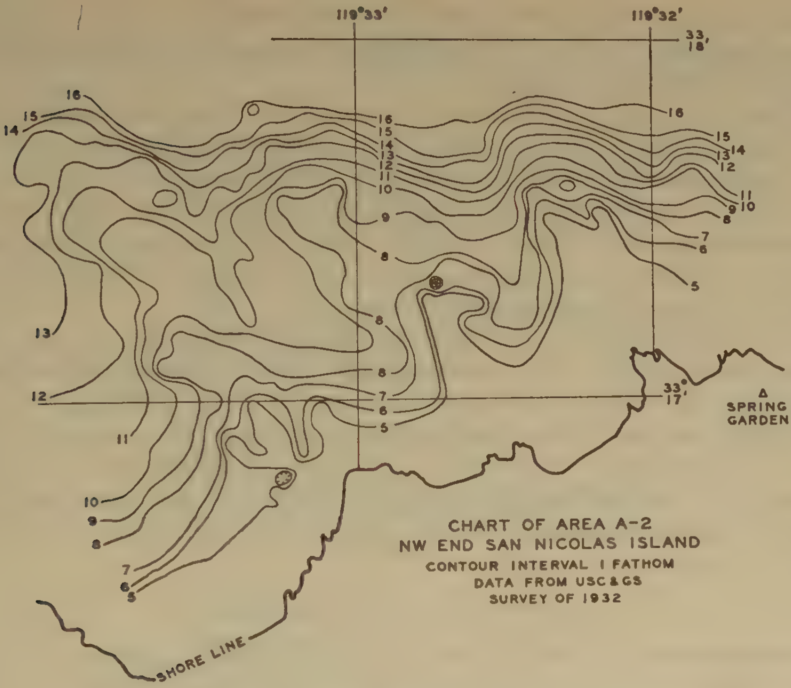
119°33'
119°32'
33° 18'
16
15
14
13
12
11
10
9
8
7
6
5
33° 17'
SPRING GARDEN
CHART OF AREA A-2
NW END SAN NICOLAS ISLAND
CONTOUR INTERVAL 1 FATHOM
DATA FROM USC&GS
SURVEY OF 1932
SHORE LINE

FIG. 14.—Bathymetry of area A-2.

the bottom relief would form ridges in harder rock and troughs in softer rock. The rocks in the troughs were examined by divers, however, and found to be sandstone like the ridges, so the difference in hardness or resistance to erosion of the rocks in the ridges and troughs may not be very large.

Sandstone was sampled at 10 of the 12 stations occupied in area A-2, and it was found at one other station, but not sampled, because one diver had to surface

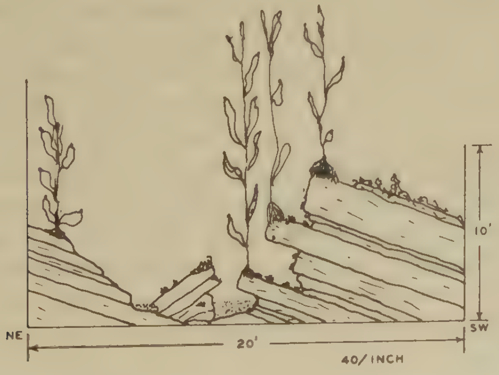
10'
NE
SW
20'
40/INCH

FIG. 15.—Typical profile of part of sea floor in areas A-1 and A-2.

when he ran out of air. Bedrock was not found at Station 5, only a blanket of loose sand at least 2 feet deep. The remarks on the significance of sampling in area A-1 apply as well to area A-2.

Bottom topography.—The sea floor in area A-1 slopes gently north and the whole area is less than 10 fathoms deep with the exception of a small part on the outer (northern) area which is about 13 fathoms deep (Fig. 13). The bottom is a fairly flat, rocky shelf with thin patches of sand between northwest-trending sandstone outcrops (Fig. 7). From air photographs it can be seen that most of the sand is near shore; probing in the sand areas indicates that the sand is less than 2 feet thick and covers a rock platform.

Area A-2 is fairly flat with the exception of a northwesterly ridge which trends through the center (Fig. 14). This ridge stands about 12–18 feet above the surrounding sea floor and is composed of sandstone which dips northeast. Depths in the area are less than 10 fathoms with the exception of the northernmost part which is at 15 fathoms. The bottom is rocky over most of the area with scattered patches of thin sand between the northwest-trending rock outcrops. Sand covers a large part of the southeast part of the area; a 2-foot probe did not strike rock below this sand.

SUMMARY OF DIVING OPERATIONS

Diving operations are summarized in Table I. Four divers spent a total of 12 hours, 18 minutes, underwater in 4 days, and 29 stations were occupied by two pairs of divers. An individual diver averaged 14 stations and 3 hours, 4 minutes, underwater. For the whole 4 days, the average number of stations occupied by a pair of divers was 3½ per day. This average is misleading, however, because no diving took place between 1030, July 8, and 1300, July 10. Excluding this time, the average number of stations occupied per day by a pair of divers was 6½.

GEOLOGICAL MAPPING WITH SELF-CONTAINED DIVING EQUIPMENT

MAPPABLE AREAS IN CALIFORNIA

The principal physical limitations on the use of self-contained diving equipment for geological mapping are the depth and temperature of the water. The maximum depth for normal operations is 120 feet. The minimum endurable temperature on the bottom is about 50°, but varies with the length of the dive and the type of exposure suit used. The temperature of California water south of San Francisco is suitable for diving although it is below the optimum temperature for maximum endurance. The area of sea floor shallower than 120 feet is about 1,000 square nautical miles between San Francisco and the Mexican border. All this area is opened to geological investigation with self-contained diving equipment. Conditions suitable for geological mapping can not be expected at all times in the area because wind and sea may hinder small-boat operations and fog may prevent locating points.

The feasibility of underwater mapping depends on the frequency of occur-

TABLE I. SUMMARY OF DIVING OPERATIONS
Appendix I

Area A-1

Boat No. 1
Total dives—7
Total time under water—1.77 hours (106 minutes)
Average time under water—15 minutes
Average depth—34 feet
Range of depth—18–63 feet

Boat No. 2
Total dives—9
Total time under water—1.65 hours (99 minutes)
Average time under water—11 minutes
Average depth—60 feet
Depth range—44–72 feet

Area A-2

Boat No. 1
Total dives—6
Total time under water—1.15 hours (69 minutes)
Average time under water—14 minutes
Average depth—45 feet
Depth range—26–66 feet

Boat No. 2
Total dives—7
Total time under water—1.58 hours (95 minutes)
Average time under water—14 minutes
Average depth—63 feet
Depth range—55–75 feet

ALL AREAS

1. Average length of dive—14 minutes
2. Average depth of dive—50 feet
3. No. of dives per diver per day—6.5
4. Average surface temperature—60° F.
5. Average bottom temperature—55° F.

rence of outcrops—which can not be determined accurately without a diving reconnaissance. The mapping at San Nicolas Island indicates encouraging prospects for the usefulness of the self-contained diving equipment elsewhere in California. The location of diving stations was in rather equally spaced east-west lines so the position of a station relative to the type of bottom was essentially random. Nevertheless outcrops were found at 26 of 28 stations, and dips and strikes were obtained at 25 stations. The stations at which outcrops were not found were all near shore where land geology could best be extrapolated to fill in the gaps. The widespread occurrence of rock-anchored kelp and the frequency of rock notations on bottom sediment charts suggest that outcrops may be found in much of the area off California which is mappable with self-contained diving equipment.

RATE OF MAPPING

The number of dives available for comparison does not justify a firm statement regarding the probable rate at which the sea floor can be mapped, but some preliminary rates are indicated by the operation at San Nicolas Island. There it was found that six stations could be occupied per day by a two-man team diving in depths of 18–75 feet. Depth did not affect the rate of diving in area A-1; for example, the team diving to an average depth of 34 feet spent an average of 15 minutes underwater and the team diving to an average depth of 60 feet required an average of only 11 minutes per dive. The principal factor affecting time was the difficulty of obtaining the large rock samples (50 pounds or more) which were required, and this varied from place to place. Ordinary hand samples could have been collected in far less time. Only 6 minutes were required to take a dip and strike and collect a hand sample in 63 feet of water at station Baker in area A-1. The writers estimate than more than six dives per day would have been possible at San Nicolas Island if hand samples had been adequate—as they would be for most geological mapping. On the other hand, the diving days were not consecutive at San Nicolas and the depths were moderate. If a program requires diving each day, six dives would appear to be the maximum number expectable because of diver fatigue.

PARTY ORGANIZATION

The basic element of an underwater mapping party is a two-man team of geologists who dive together—so called "buddy" divers. Two men per dive are required for maximum safety, and little is lost in efficiency because the tasks of mapping can be carried on simultaneously. At San Nicolas one diver measured the dip and strike while the other took a rock sample. Inasmuch as the divers are in the water together, a third man is required to tend the boat, follow the divers' bubbles, and determine positions. If a party consists of three men operating from a small boat based on shore, the third man (who would normally be party chief) should also be trained as a diver. He should normally make a few reconnaissance dives in an area in order to plan the mapping program; he should also be prepared to substitute for one or two days for one of the regular divers who might be incapacitated for diving by a minor respiratory illness. Judged by the San Nicolas operation, the party chief should not dive on ordinary days for the following reasons.

1. The man in the boat is the only one who has time to consider the results of the day's diving and to plan the next step because the divers are too busy diving and readying equipment between dives to grasp all the significance of the results they are obtaining. After a day of diving a diver is too fatigued to evaluate and plot the day's work and plan for the next day's operations.

2. The party chief must be prepared to call for a rest period or to stop the day's work if he believes that the divers are becoming too tired for safe operations or if he believes that changes in the weather indicate that small-boat operations may become hazardous.

If the area to be mapped is too far from shore or from a harbor to use a small open boat, a small cabin cruiser or its equivalent will be required. One or more crew members will be necessary depending on whether the ship returns to port each day or anchors in the area for several days. The minimum team of three geologists may be used, but two teams, such as were used at San Nicolas, may be more economical. In exposed areas, for example, it may be expedient to carry out diving as rapidly as possible whenever favorable weather conditions permit small-boat operations.

METHOD OF MAPPING

Several steps should precede geological mapping of an area of the sea floor by routine diving: reconnaissance diving to determine the applicability of the method, establishment of known points for location, preparation of a detailed bathymetric chart, detailed geological mapping of the adjacent shore, and possibly aerial photography.

Inspection of bottom notations on published charts gives some indication of the occurrence of bare outcrops which can be studied by divers. This information may be supplemented by sampling the bottom or by dragging a soundfish (LaFond, Dietz, and Knauss, 1950). However, a more direct method of feasibility study is to make a few preliminary dives at widely spaced points in the area. This method should require no more than a day in the field for a few square miles.

If an area appears promising, a network for location can be established. Several systems of accurate near-shore locations are available (Adams, 1942) but the writers have found control by horizontal sextant angles to be most satisfactory. The method is inexpensive, accurate, and reliable. As used in area A-1 at San Nicolas, buoys are located from a triangulation network on land, and the buoys are used as known points for locating the diver stations. Shore control alone is adequate for work within ½ mile of shore. A covered boat with a plotting table is desirable if positions are to be determined at the time of diving.

A detailed bathymetric chart should next be prepared by the use of a portable recording echo-sounder; it is the equivalent of a contoured chart on land and is equally necessary for plotting. This procedure was not followed at San Nicolas only because neither of the available instruments was working. An equivalent, although far less detailed, bathymetric chart was made from the spot soundings on U. S. Coast and Geodetic Survey boat sheets, provided through the courtesy of Cdr. W. F. Malnate. It was evident, however, that a survey would have shown the location and extent of the resistant strike-ridges which were found by diving, and also the boundaries of the flat sand patches between the ridges. With this information on hand, the diving stations could have been located at significant points rather than at random ones. The bathymetric survey thus has the added advantage of providing a base map which can be used to plan the details of procedure for efficient diving.

Aerial photographs may also be useful even though the outcrops are covered with water. At the very least the photographs would show the position of kelp which in turn would indicate outcrops. At best the water surface might be smooth enough so that the bottom would be visible to depths almost as great as the maximum routine diving depth. This possibility is rather surprising considering the difficulties in seeing the bottom on aerial photographs which were encountered during World War II amphibious operations. Nevertheless, the bottom was visible to a depth of at least 70 feet off San Nicolas on photographs taken at about 12,000 feet with a K-17 camera with a 12-inch focal length. Likewise aerial photographs have shown the bottom at a depth of 90 feet off La Jolla (Conrad Limbaugh, personal communication).

Procedures of geological mapping with self-contained diving equipment are flexible: a plan might include a reconnaissance and then a survey in sufficient detail for the desired accuracy. Mapping underwater differs from mapping on land chiefly in that visibility is only 10–40 feet. The diver is as mobile as a hummingbird, but he works in the equivalent of a dense fog. His mobility makes it possible to inspect every inch of an outcrop 40 feet high, yet he usually is unable to see a similar outcrop 40 feet away. Consequently diving stations give information regarding unconnected points. Upon completion of a geological reconnaissance like the one off San Nicolas, hand specimens and dips and strikes are available at various points. Preparation of a preliminary geological map requires interpolation between the points. In many respects the problem can be treated like subsurface mapping and correlations can be made by normal means.

A preliminary geological map might show the approximate locations of contacts and possible faults, and the broad outlines of folds. More detailed mapping could combine two approaches. Spot dives could be spaced more closely and concentrated at critical points, or divers could swim along outcrops. Bottom topography would determine which method would be more practical. Swimming along a contact could be done as follows.

1. The divers locate a contact by diving on its approximate position, and proceed to swim along it. They release a small buoy.

2. The party chief rows to the bouy and locates its position. He then follows the bubbles rising from the divers and obtains fixes periodically.

3. Depending on the ability of the divers and the depth, the contact may be followed for 500–1,000 feet on one dive.

4. The boat would then be anchored until the divers are rested enough to resume following the contact.

The same general method can be used to locate contacts and measure sections by swimming perpendicular to the strike. A line could be laid along the bottom as a guide, but experienced divers can follow a bearing by using an underwater compass. The divers would be required to carry several small buoys with attached light line and weights which would give neutral buoyancy; sample bags would be attached to the line near the weights. Upon locating a contact, a sample of the rock on the far side of the contact would be placed in the bag, and the buoy would be released to carry the line to the surface. The boatman would obtain the position of the buoy, and haul in the sample and weight. He would then follow the bubbles until the next buoy appeared.

CONCLUSIONS

A geological reconnaissance of 2 square miles of the sea floor off San Nicolas Island, California, indicates that self-contained diving equipment can be used by properly trained[4] geologists to map the geology of submarine areas.

The equipment opens 1,000 square miles of the sea floor off California to investigation by modifications of normal mapping techniques. The detail obtainable appears greater than by any other means of underwater mapping.

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[4] The necessity for proper training is discussed in an accompanying report by Dill and Shumway ("Geologic Use of Self-Contained Diving Apparatus," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 38, No. 1, January, 1954, pp. 148–57). Self-contained diving equipment is deceptively easy to use. In 5 minutes a man can learn enough to be able to kill himself.

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THE CONTROL OF STREAM OUTLETS BY WAVE REFRACTION

WILLARD BASCOM

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GEOLOGICAL NOTES

THE CONTROL OF STREAM OUTLETS BY WAVE REFRACTION[1]

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The importance of wave refraction as a mechanism for distributing the sea's energy along the shore lines of the world can scarcely be overstated, yet some of the implications seem not to be fully appreciated. The object of this paper is to point out that submarine topography and shore-line configuration may control subaerial features. For many years before wave characteristics had been reduced to usable simple numbers and the phenomena of refraction mathematically described, geologists spoke in qualitative terms about waves "attacking headlands in great force." Mariners used to say "the points draw the waves," and, of course, they traditionally took advantage of the comparative quiescence of bays to anchor their ships. The difference in wave energy reaching the shore of a headland versus that reaching the shore of a bay is quite apparent to even a casual observer, and the tendency of waves to straighten coasts has long been recognized. The refraction process can also make certain subtle modifications of shore lines, and on a comparatively young shore line, such as that of the United States Pacific Coast, these are observable.

Consider the process of wave refraction. In its simplest terms, refraction is the bending of waves in shallow water to approximate the shape of the underwater contours. Swell (waves from distant storms with periods, T, of 6–18 sec.) approaching a shore line moves in deep water, with parallel crests at a constant speed. Upon reaching a depth that is less than half the wave length, it "feels bottom" and is slowed down so that successive crests are closer together; as the depth decreases, the waves move ever slower, which makes their crests bend ultimately to parallel the shore line. By graphically indicating the successive positions of a wave front at equal increments of time, a clear picture of the changing direction of wave advance can be created. Such a drawing is called a *refraction diagram*. In deep water, equal lengths of wave front represent equal amounts of energy; as the waves are bent, however, the energy is redistributed and may converge or diverge, depending on the shape of the submarine topography. In order to illustrate the distribution of energy, orthogonals (lines normal to the wave fronts) are drawn which show the direction of energy propagation. If the deep-water wave front is divided into equal segments, the orthogonals then divide equal portions of wave energy. Once refraction diagrams have been prepared, refraction coefficients can be computed from measurements taken directly from the drawing. In such computations,

$$H(\text{the height of a wave at any point}) = H_0\sqrt{\frac{b_0}{b}},$$

where the zero subscript designates the deep-water[2] condition and b is the distance between orthogonals. Refraction coefficients, $\sqrt{b_0/b}$, can thus be conveniently used to compare wave heights at various points along the shore line.

Wave refraction is controlled by the period of the waves, their direction of motion,

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[1] Contribution from the Scripps Institution of Oceanography, new series, no. 675. Manuscript received September 8, 1953.

[2] Waves in deep water which are as yet undisturbed by refraction offer a convenient standard of reference.

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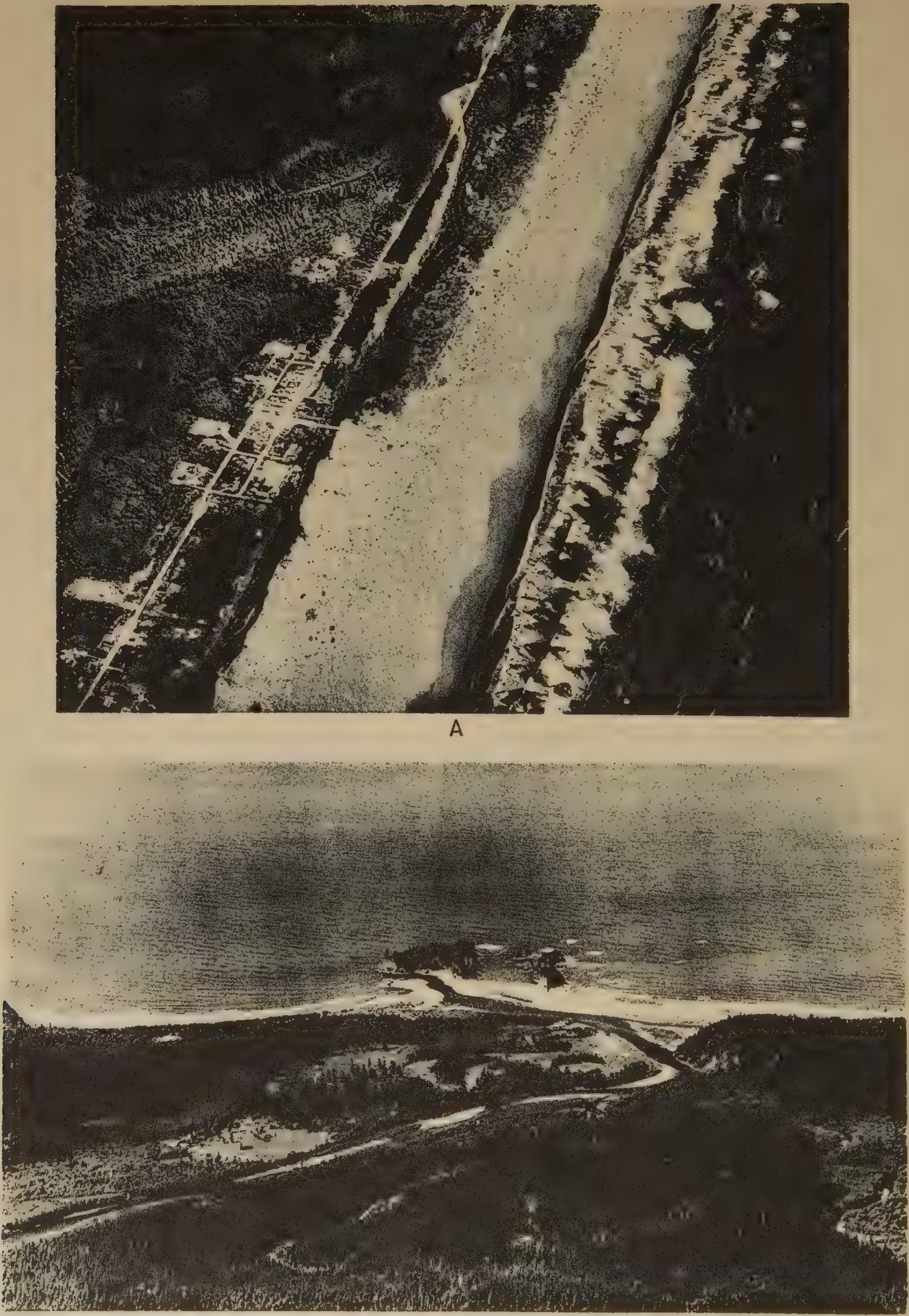

A

B

Stream and Shoreline Features

and the underwater contours. The examples shown here each represent a sort of composite situation made to illustrate a point; similar actual situations are not only possible but rather common (pl. 1).

This procedure of illustrating only a single wave condition for each topography allows the fairly obvious objection that a change in wave period or direction would alter the distribution of energy. This is true, but it must be realized that on many coasts the direction of the influential swell remains constant for much of the year. On the United States Pacific Coast, for example, the wave climate centers about swell from the northwest with a period of 12 seconds (Scripps Inst. Oceanography rept. no. 68) because many of the wave-generating storms seem to originate in about the same position with respect to the coast.

Now consider the effect of waves in building beach structures of sand, shingle, and cobbles. The waves which ultimately reach any beach after having been refracted are responsible for shaping it; they control the beach slope, the number of bars, and, to some extent, the size of the particles (Johnson, 1919; Shepard, 1948; Bascom, 1951). Most important to the subject at hand, they control the height of the berm. A berm is a nearly horizontal deposit of beach material brought ashore by the waves, and its height (above the mean sea-level at the time it was formed) has been shown (by Bagnold, 1940) to be 1.3 as high as the deep-water height[3] of the waves that formed it. Field observations by the author substantiate this figure quite closely; the lowest berm is certainly found in the most protected spot, where the waves that formed it were lowest. Since the berm height is directly related to the wave height on the beach, which is itself a function of the refraction coefficient, it is evident that relative berm heights can be obtained from refraction diagrams.

The ability of storm waves to dam stream mouths with great quantities of sand and completely shut off all save subterranean flow is well known. The Rogue River of Oregon and the Salinas River of California are examples of streams which flow intermittently for this reason; in the dry season many other streams are so dammed. As soon as the flow into the sea is stopped, a lagoon forms, and the water level rises slowly. Often a large temporary lake or an elongated "moat" will form; these may parallel the shore line for a considerable distance and seemingly threaten to break the dam anywhere along the beach. When the lagoon water surface reaches the lowest point in the crest of the dam (berm), it cuts a little channel, which rapidly widens and deepens into a major breakthrough. The lagoon waters race seaward, and a new entrance of the stream into the sea exists which may last for a month or a season or a cycle of beach change. As used here, the words *dam* and *berm* are equivalent, for the berm thrown up by wave action has held back the stream. The presence and position of a low point in the berm (where the breakthrough occurred) is, as we have seen, controlled by the height of the waves, which are in turn controlled by the submarine topography. Thus, vicariously, the wave refraction has influenced the position of the stream entrance.

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[3] Notice that Bagnold's deep-water height is related only to the change in height of an unrefracted wave approaching shore. The actual deep-water height of the waves on a beach is this theoretical H_0 divided by the refraction coefficient.

PLATE 1

A, At Ocean City, Washington, a small stream has been dammed by the sandy beach material and forced to flow over 1 mile to find outlet. An extremely uniform underwater gradient allowed no opportunity for refraction to influence this outlet, but it is evident that any small difference in the beach structure might allow a breakthrough.

B, The Quillayute River in northern Washington meanders across a rather wide floodplain and approaches close to the beach at a point ½ mile from its ultimate outlet. The entrance of the river into the ocean in the most protected location behind James Island (as indicated by the relatively small amount of white water showing) can be explained by wave refraction. Jetties now confine the stream outlet to the southerly side of the island.

It is apparent that the mechanism suggested here cannot apply everywhere, since many streams are highly restricted in their lateral movement at the shore line by confining rocky walls. However, for the many cases where a stream is free to meander over a coastal plain perhaps these notes will explain certain curious circumstances. It is believed that the specific examples accompanying the three general cases are sufficient to prove the point.

Figure 1 is a refraction diagram which shows waves refracting as they approach a section of coast which includes a headland with an offshore reef and an embayment. As the wave fronts fit themselves to the submarine contours, the wave energy converges to attack the reef and headland; notice that the same amount of energy which was expended on a very short shore line at the headland is spread over a comparatively long shore line in the embayment. The numbers at the shore line are refraction coefficients ($\sqrt{b_0/b}$)—obtained by measuring the distance between orthogonals in deep water (b_0) and at the beach (b); these indicate both relative wave height and berm height. A stream approaching this hypothetical shore across a flat topography would certainly enter the sea at the place where the refraction coefficient is only 0.57, for here the berm will be lowest. It is interesting to observe that on the United States Pacific Coast the Sooes River, the Ozette River, the Coos River, the Coquille River, and the Garcia River (Point Arena) are clearly like the situation illustrated. San Diego Bay entrance is similar in the sense that the

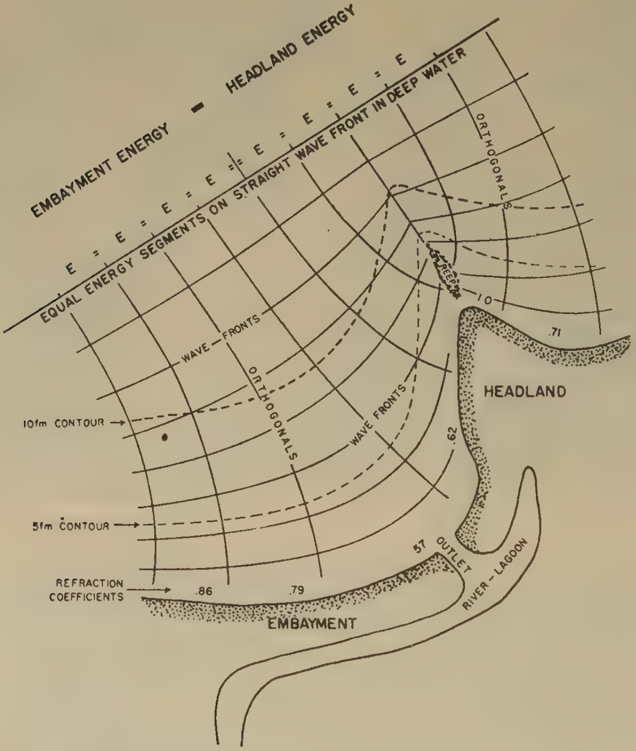


FIG. 1.—Low berm adjacent to a headland

natural connection to the sea is in the obviously most sheltered position behind Point Loma. On the Oregon coast there are many streams which have apparently exercised this choice and selected an outlet near a headland, where the wave-energy level is lowest.

Figure 2 illustrates a wave train approaching a sandy coast line which is protected in part by a small island or large offshore rock. A tombolo has formed in the lee of the rock, where greatly reduced wave action has allowed sand to deposit. Here, as indicated by the refraction coefficients on the shore of the tombolo, is a natural place for a stream to enter the ocean; in a seeming paradox, it will flow directly toward the rock, for that is the line of ultimate least resistance. This curious situation, pointed out to the author by John Isaacs in a personal communication in 1950, is observed in nature at the Quillayute River and the Raft River in Washington, the Neskowin River in Oregon, and Morro Bay entrance in California.

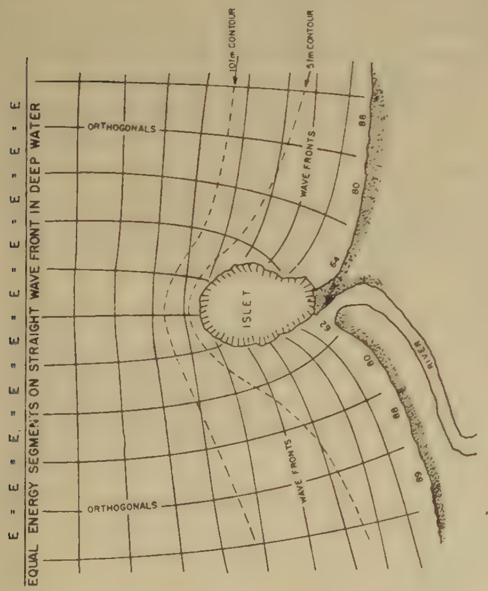
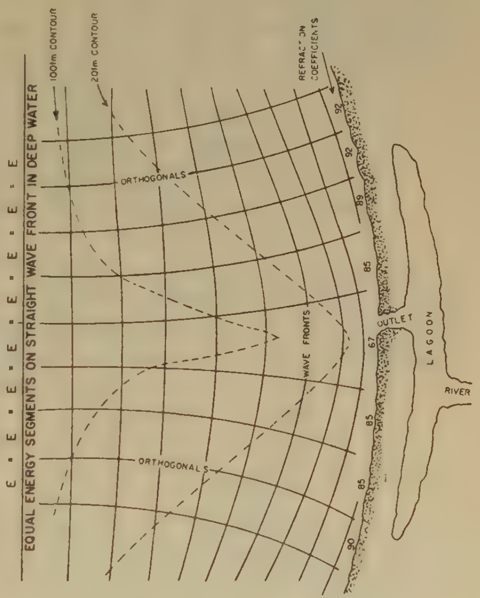

E - E - E - E - E - E - E - E - E - E - E
EQUAL ENERGY SEGMENTS ON STRAIGHT WAVE FRONT IN DEEP WATER
10fm CONTOUR
5fm CONTOUR
ORTHOGONALS
WAVE FRONTS
88
80
64
ISLET
62
60
88
89
RIVER
WAVE FRONTS
ORTHOGONALS

FIG. 2.—Low berm in lee of an islet

Figure 3 shows a sequence of waves approaching a shore line over a submarine canyon (two contour lines indicated by dashes). As in the previous examples, the wave energy is redistributed by the effect of the bottom eccentricities, and opposite the head of the canyon there is a quiescent zone, where a low refraction coefficient exists. By the same reasoning as before, a low berm can be expected at this point, and any stream which approaches the sea and is dammed will ultimately break out at this point.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EQUAL ENERGY SEGMENTS ON STRAIGHT WAVE FRONT IN DEEP WATER
100fm CONTOUR
20fm CONTOUR
REFRACTION COEFFICIENTS
ORTHOGONALS
92
92
89
85
OUTLET
LAGOON
67
WAVE FRONTS
RIVER
85
ORTHOGONALS
85
90

FIG. 3.—Low berm opposite the head of a submarine canyon.

The connection between submarine canyons and subaerial valleys has long been pondered, and the presence of stream mouths opposite canyon heads has been used in certain hypotheses to link the origin of canyons with stream erosion. It is not the author's intention to become embroiled in the great submarine-canyon controversy but only to point out that such canyons may influence the position of stream entrance into the ocean. The possibility that the canyon is older than the stream or that it came into existence at a time when the stream was

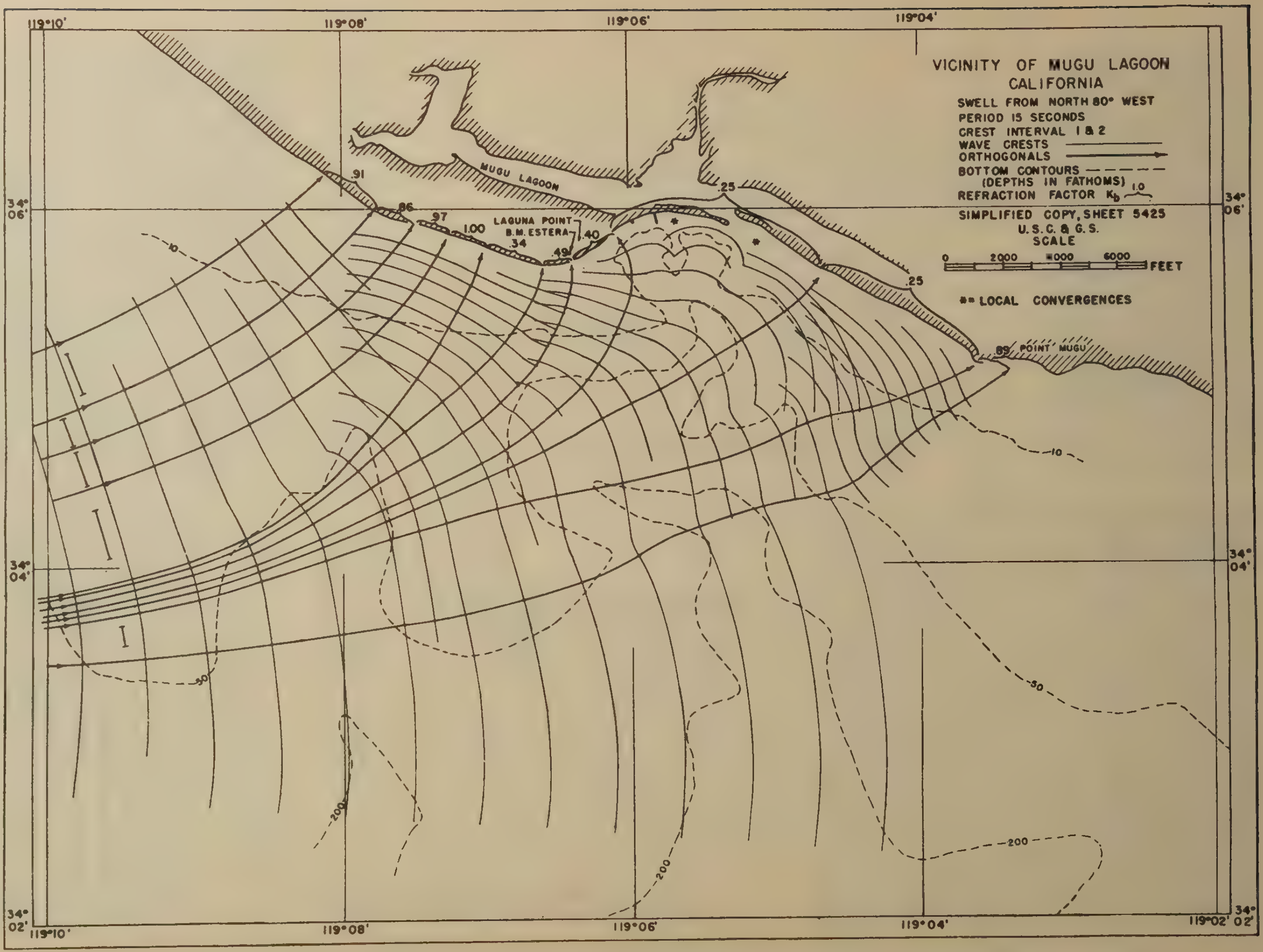
VICINITY OF MUGU LAGOON
CALIFORNIA
SWELL FROM NORTH 80° WEST
PERIOD 15 SECONDS
CREST INTERVAL 1 & 2
WAVE CRESTS
ORTHOGONALS
BOTTOM CONTOURS
(DEPTHS IN FATHOMS)
REFRACTION FACTOR K_b 1.0
SIMPLIFIED COPY, SHEET 5425
U.S.C. & G.S.
SCALE
0 2000 4000 6000 FEET
* = LOCAL CONVERGENCES
MUGU LAGOON
LAGUNA POINT
B.M. ESTERA
POINT MUGU
.91
.86
.97
1.00
.34
.49
.40
.25
.25
.89
10
50
200
119°10'
119°08'
119°06'
119°04'
119°02'
34° 06'
34° 04'
34° 02'

FIG. 4.—Wave refraction at Mugu Canyon (taken from Technical Memo no. 14, Beach Erosion Board, by D. L. Inman)

free to meander suggests that, although the origins of stream and canyon may be totally unrelated, the canyon may have exercised enough control of the shore-line forms to have reoriented the stream and thus make it appear that the origins of the two are related.

Mugu Canyon, illustrated for a fairly typical wave condition by figure 4 (from Inman, 1950), seems to control the outlet of the lagoon made by the damming of Calleguas Creek to an unusual degree. Here damming of the outlet and the rebreaching sometimes occur twice a year—but always at about the same place, although the lagoon closely parallels the coast for several miles. According to Inman in a personal communication, after the breakthrough of the lagoon waters, the prevailing littoral transport of the sand to the south and east builds the westerly side of the spit at the entrance, and tidal currents erode the easterly side, making the entrance migrate to the southeast. The outlet which originated opposite the canyon head may thus move a mile or more along the coast until it is again in a zone of comparatively high wave action and is more easily dammed by the berm resulting from the next storm. The cycle then repeats—the lagoon rises and breaks through again opposite the canyon head.

It is thus seen that submarine topography and oceanic forces do influence subaerial land forms. Geologists concerned with the study of coast lines are encouraged to consider the possibility that the small differential forces in the ocean, including those which are not in ascendancy at the present time, may have shaped or modified forms or situations otherwise unexplicable.

Acknowledgments.—The author wishes to express his appreciation to Drs. R. Revelle, F. Shepard, and D. Inman, of the Scripps Institution of Oceanography, for a critical reading of this paper.

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(*Reprinted from Nature, Vol.* 173, *p.* 169, *January* 23, 1954)

Pigmentation of the Jellyfish, *Pelagia noctiluca**

THE striking pigmentation of a large form of the purple-striped Scyphomedusan *Pelagia noctiluca* (Forskål), which is encountered occasionally in the coastal waters of California, involves three main pigments—magenta, brown and blue.

The blue is found in cells of the exumbrellar epidermis and the gonadial endoderm, as large rounded inclusions measuring up to 7 μ in diameter. It is found also in the lips. When fresh, the gonadial pigment shows absorption maxima in the visible range at 632·5, 590 and 560 mμ, but it is unstable, changing rapidly to a reddish-orange colour on treatment with boiling water, ethanol or formaldehyde. When extracted from autolysed tissue, the pigment exhibits a shift of its absorption maxima to 620, 577 and 545 mμ. The blue pigment of the exumbrellar epidermis, though appearing similar histologically, shows a different absorption spectrum, with a single broad maximum in the visible region at 545–550 mμ. The pigment from the lips is similar. All were rapidly attacked by trypsin, becoming cloudy orange, while the absorption maxima shifted progressively towards the blue, eventually disappearing from the visible region.

The brown pigment occurs in the exumbrellar epidermis, the mesoglœa and in the gonadial endoderm. It is stable and shows no absorption maximum, but a steadily increasing absorption towards the ultra-violet. In size and disposition, the granules resemble those of the magenta pigment.

The magenta pigment is predominant, and in the exumbrella is exclusively extracellular, being found in the superficial layers of the mesoglœa. It occurs as ellipsoidal granules 0·2–0·6 μ in length, either free or associated with coloured or colourless spheroids measuring some 3 μ in length, in a fashion reminiscent of the melanin granules in *Diadema*[1] and *Holothuria*[2]. Its chemical properties have been studied in some detail.

Although soluble in water, dilute acids and alkalis, the magenta pigment is insoluble in several organic solvents. It is non-dialysable, and the colour does not change when the pigment is dissolved in phos-

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* Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 676.

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phate buffers from pH 10·0 down to weakly acidic values. When dissolved in buffer at pH 9·0, it shows a single rounded absorption maximum in the visible region at 490 mμ, which moves progressively toward the shorter wave-lengths when the pigment is hydrolysed by alkali or trypsin, or is extracted from autolysing tissue. After such treatment the pigment becomes brown, showing an absorption spectrum with no peaks, but with a steadily increasing absorption toward the shorter wave-lengths. These properties indicate a chromoprotein.

Prolonged hydrolysis with trypsin yields a deep reddish-brown chromogen which is precipitated by dilute alkali and, after washing and redissolving in dilute hydrochloric acid, shows a maximum absorption at 380 mμ. It is insoluble in a wide variety of organic solvents, is decolorized by the combined action of zinc dust, sodium acetate and acetic anhydride, and reduces ammoniacal solutions of silver nitrate. It thus behaves somewhat like a melanoid; unlike the common melanins, however, this pigment contains no sulphur.

Further tests indicated that the pigment contains nitrogen and a substituted phenol, but no aldehyde or carbohydrate groupings. It gave no reactions for proteins, tyrosine, tryptophan, arginine or other α-amino-acids or purines. The chromogen (known to be tryptophan-free) gave, after treatment with fused potassium hydroxide, a clear positive Ehrlich's reaction for the indole grouping, and a pyrrole reaction on roasting. The colour which developed in the indole reaction, when compared spectrophotometrically with that given by melanin from black feathers or by pure tryptophan, showed closely similar absorption spectra with maxima in the range 530–540 mμ.

These biochromes from *Pelagia* are sharply distinguished from the 'pelageine' described (from an unidentified species) by Griffiths and Platt[3]; yet in certain respects they are like some of the scyphozoan pigments described by earlier workers. Such findings were reviewed by Fox and Pantin[4], who pointed out that typical melanism is rare in cœlenterates, and is recognized in only a few of the Anthozoa. Certainly no clear evidence has yet been obtained for the existence of tyrosinase in breis from either coloured or colourless portions of this medusa, using both monohydric and polyhydric phenols as buffered substrates.

We are indebted to Prof. T. A. Geissman, of the University of California at Los Angeles, who demonstrated the indole reactions. A full account of the investigation will be published elsewhere.

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Sept. 25.

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[1] Jacobson, F. W., and Millott, N., *Proc. Roy. Soc.*, B, **141**, 231 (1953).

[2] Millott, N., *J. Mar. Biol. Assoc. U.K.*, **31**, 529 (1953).

[3] Griffiths, A. B., and Platt, C., *J. Amer. Chem. Soc.*, **17**, 877 (1895); *C.R. Acad. Sci., Paris*, **121**, 451 (1895).

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Separatum
EXPERIENTIA
VERLAG BIRKHÄUSER, BASEL, SCHWEIZ

Vol. X/4, 1954 – pag. 185

A Biliverdin-like Pigment in the Skull and Vertebrae of the Ocean Skipjack, *Katsuwonus pelamis* (Linnaeus)[1]

The occurrence of blue-green pigments in the skeleton of teleosts such as *Cottus, Belone, Zoarces, Strongylura* and others, has been reported by several workers[2]. The pigments have not been identified, although their similarity to bile pigments has been demonstrated. CAGLAR[3] believes that the skeletal pigment of *Belone* is biliverdin.

On rare occasions, the catches of skipjack in waters of Baja California include individuals whose endoskeletons, especially the skull and vertebrae, are strikingly green or blue-green. Such an individual was sent for our examination through the courtesy of the Van Camp Sea Food Company and M. B. SCHAEFER of the International Tropical Tuna Commission. Four years earlier, one of us (D.L.F.) had studied the pigment from the bony parts of a similarly coloured individual of the same species, made available through the kindness of HARRY C. GODSIL, of the California State Fisheries Laboratory.

Since the properties of such a pigment occurring in the *Katsuwonidae* have not been described, we have taken the opportunity of examining them. Unfortunately, both of the specimens which became available had been cooked, so that we cannot describe the distribution of the pigment except in the axial skeleton which was of a pea-green color.

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 677.

[2] M. CAGLAR, Nature *155*, 670 (1945). – D. L. FOX, *Animal Biochromes and Structural Colours* (Cambridge University Press, 1953), p. 279. – H. WILLSTAEDT, Enzymologia *9*, 260 (1941) (Chem. Abstr. *36*, 842).

[3] M. CAGLAR, Nature *155*, 670 (1945).

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In the vertebral column, it appeared especially abundant in the centra, neural arches and in the base of the haemal arches. Less appeared in the neural spines, and none in the notochord. In the skull, it appeared in both dermal and cartilage bones, being especially conspicuous in the prefrontals, pre-maxillae, maxillae, dentaries, median ethmoid, supra-orbitals, vomers, exoccipitals, articulars, quadrates and in the otic series. It was conspicuous in parts of the parietals, hyomandibulars, the opercular series, the branchial arches and in the sclerotic of the eye. Less was present in the frontals, lachrymals and parasphenoid; little was present in the supra-occipital.

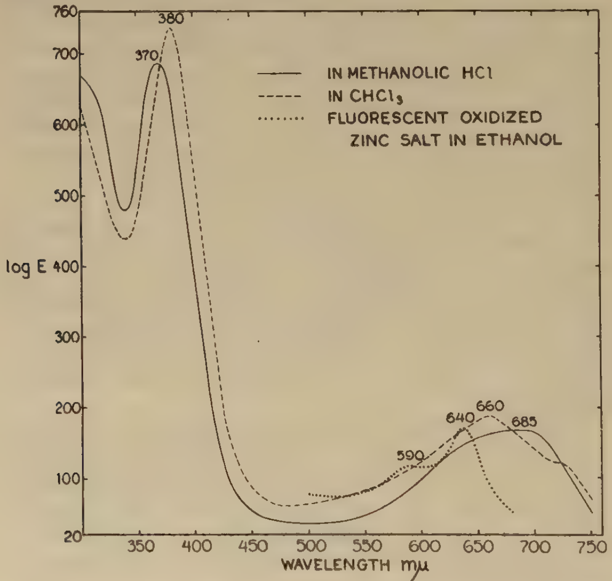

Fig. 1.–Comparative light absorption of the endoskeletal pigment dissolved in acid methanol and in chloroform. The absorption of the oxidized zinc complex dissolved in ammoniacal ethanol is also shown.

From the vertebrae, stripped of adhering flesh, washed in water and comminuted in a blender, the pigment was leached with methanol containing concentrated hydrochloric acid (9:1 by volume). The blue-green pigment was readily extracted from this solution by moderate dilution while agitating with chloroform.

Pigment	Absorption maxima (mμ)		Absorption minimum (mμ)
	I	II	
Skeletal pigment of *Katsuwonus* in HCl-methanol	680–690	370	510
Biliverdin hydrochloride in HCl-methanol (Lemberg and Legge) .	680	377	approx. 500
Chloroform solution of biliverdin acidified by HCl-methanol (Tixier)	675	–	492
Skeletal pigment of *Katsuwonus* in chloroform	660	380	480
Methanolic ester of biliverdin in chloroform (Tixier)	665	384	490

The acid methanolic solution showed no fluorescence in ultra-violet light, but showed absorption peaks at 680–690 mμ and at 370 mμ and a minimum at 510 mμ (Fig. 1). The chloroform solution showed peaks at 660 and 380 mμ and a minimum at 480 mμ (Fig. 1). The absorption spectra thus resemble very closely those of biliverdin, a bilatriene tetrapyrrole (see Table, showing data from Lemberg and Legge[1], Tixier[2] and this paper).

Supporting these indications is the fact that the skeletal pigment, dissolved in chloroform, or in the form of a dry film, showed a clear positive reaction to the Gmelin test using fuming nitric acid. In chloroform the highly characteristic red, violet and blue colours appeared in the solvent, but treatment of the dry film on a porcelain dish yielded only the red colour.

The skeletal pigment dissolved in ammoniacal ethanol, to which zinc acetate and a few drops of iodine were then added, formed a characteristic blue-green solution showing an intense red fluorescence in ultraviolet light and marked absorption in the orange to red region of the spectrum (see Fig. 2). Such a reaction is characteristic of bilatrienes subjected to similar treatment (LEMBERG and LEGGE[1]).

The absorption spectrum of the zinc complex of the oxidized pigment in ammoniacal ethanol showed maxima at 590 and 640 mμ, agreeing with those given by TIXIER[2] for the zinc complex of an oxidized biliverdin methyl ester in neutral alcoholic solution. Moreover, the absorption

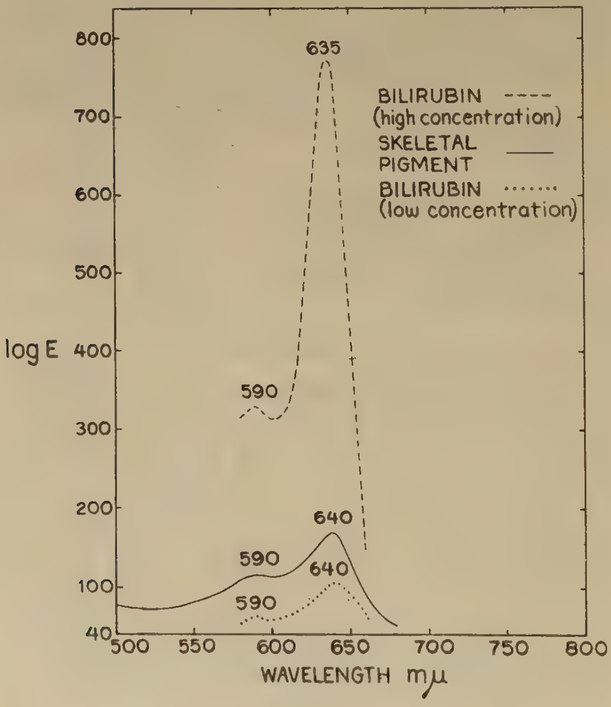

Fig. 2.–The light absorption of the oxidized zinc complex derived from the endoskeletal pigment, compared with that of solutions of the similar complex derived from bilirubin. All solutions were in ammoniacal ethanol.

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[1] R. LEMBERG and J. W. LEGGE, *Haematin Compounds and Bile Pigments* (Interscience Publishers, New York, 1949), pp. 116–117.

[2] R. TIXIER, Ann. Inst. Oceanogr. *22* (Fasc. 5), 344 (1945).

properties of such solutions, in the range 580–660 mμ, correspond very closely with those exhibited by bilirubin when oxidized and subjected to the same treatment (Fig. 2). Indications are thus confirmed that the skeletal pigment of *Katsuwonus* is closely similar to biliverdin.

Two reactions of the pigment deserve mention. First, despite the foregoing, it consistently failed to show a pyrrole reaction when roasted, since the fumes failed to redden a pine splinter moistened with concentrated HCl. In view of this, the test was repeated on skatole, haematin and bilirubin. Though skatole gave a marked positive reaction, haematin and bilirubin failed completely. The negative result given by the skeletal pigment was perhaps, therefore, not surprising, and the test appears to have limited application.

Second, the skeletal pigment was found to react with benzidine and hydrogen peroxide, producing a pea-green colour (cf. WILLSTAEDT[1]). The reaction was feeble and was shown by solutions of the pigment in water as well as those in ethanol. In view of this, and of the fact that such a reaction is characteristic of tetrapyrroles with a closed ring, it would appear that the reaction is not due to the main mass of pigment, but to accompanying traces of the porphyrin type.

The skeletal pigment thus shows the characteristics of an open chain tetrapyrrole of the bilatriene type, resembling biliverdin. Nothing is known of its metabolism.

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Division of Marine Biochemistry, Scripps Institution of Oceanography, University of California, La Jolla, Calif., November 9, 1953.

Zusammenfassung

Im Skelett von *Katsuwonus pelamis* kommt vereinzelt ein blaugrünes Pigment vor, dessen Verteilung im Endoskelett beschrieben wird. Das Pigment kann mit saurem Methanol extrahiert und in Chloroform über-

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[1] H. WILLSTAEDT, Enzymologia *9*, 260 (1941) (Chem. Abstr. *36*, 842).

[2] Guggenheim Research Fellow from University College of the West Indies, Jamaica.

geführt werden. Die saure Methanollösung des Pigments zeigt Absorptionsmaxima bei 680–690 und 370 mμ, die Chloroformlösung bei 660 und 380 mμ. Sowohl trockene Filme des Pigments als auch die Chloroformlösung geben eine positive Gmelinsche Reaktion, und der oxydierte, in ammoniakalischem Äthanol gelöste Zinkkomplex des Pigments zeigt im ultravioletten Licht eine intensive rote Fluoreszens und Absorptionsmaxima bei 590 und 640 mμ. Das Pigment besitzt somit die Eigenschaften eines Bilitrientetrapyrrol und ähnelt weitgehend dem Biliverdin.

(SYMPOSIUM ON OCEANOGRAPHIC INSTRUMENTATION, National Research Council Publication 309, 1954. Not available for distribution.)

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(SYMPOSIUM ON OCEANOGRAPHIC INSTRUMENTATION, National Research Council Publication 309, 1954. Not available for distribution.)

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(SYMPOSIUM ON OCEANOGRAPHIC INSTRUMENTATION, National Research Council Publication 309, 1954. Not available for distribution.)

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681

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1

Studies of Cyprinodont Fishes. XXI. *Glaridodon latidens,* from Northwestern Mexico, Redescribed and Referred to *Poeciliopsis*[1]

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(Plate I; Text-figure 1)

Introduction

AMONG the most troublesome jobs faced by the systematist is the proper allocation of old species based solely on insufficient and imperfect type material from an unknown or indefinite locality. One such species, *Glaridodon latidens* Garman, from "Chihuahua, Mexico," has posed an enigma since no specimens fitting the description have heretofore been brought to light from northern Mexico. The generic placement of this fish has always remained in doubt.

On the basis of a critical comparison of the four female type specimens with the extensive series of *Poeciliopsis* in the University of Michigan Museum of Zoology (UMMZ), we identify *Glaridodon latidens* with confidence as a valid species of the genus *Poeciliopsis.* It is assumed that the type locality of *P. latidens* is not in the Rio Grande drainage, as has commonly been supposed, but is probably in the headwaters of the Rio del Fuerte. This Pacific-drainage stream rises in Chihuahua, although the material we interpret as *latidens* is entirely from the adjacent states of Sonora and Sinaloa, through which this stream and others inhabited by the species also flow. It is one of the common poeciliids in the Pacific drainage of northwestern Mexico.

Acknowledgments

We are greatly indebted to the authorities of the Museum of Comparative Zoology (MCZ) of Harvard College, and particularly to Mrs. M. M. Dick, for a loan of the types of *Glaridodon latidens* and for catalogue data concerning these specimens. We also wish to thank the authorities of the Chicago Natural History Museum (CNHM), and especially Loren P. Woods, for the loan and exchange of comparative material. Boyd W. Walker, of the University of California at Los Angeles, kindly sent us series of *Poeciliopsis* from northwestern Mexico. The photographs were taken by Photographic Services, University of Michigan, and slightly retouched by William L. Brudon, artist of the University of Michigan Museum of Zoology. Funds for obtaining the photographs were provided through a research grant to the junior author from the Horace H. Rackham School of Graduate Studies.

Status of Glaridodon latidens

Types.—The existing type material (MCZ No. 1307) consists of four adult females, about 22

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 681, and from the Museum of Zoology, University of Michigan.

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to 25 mm in standard length. The specimens are stained brown, somewhat shrivelled, and the fins are mostly broken. One individual has half of the lower jaw pulled off and another has both jaws pulled off, presumably by Garman when he examined the dentition (see Garman, 1895, Pl. V, Fig. 11). There is a small hole through the side of each specimen, and one has been dissected on the left side to expose the vertebrae.

Type Locality.—In response to a query regarding the type locality, Mrs. Dick wrote on December 5, 1952, as follows:

> The specimens of *G. latidens* were catalogued by F. W. Putnam in April, 1861, as being from Chihuahua, Mexico, and the preceding entry, 1306, also was recorded from there, with a reference to an original number of 1 for 1307 and 1-3 for 1306. These must be original numbers in a small collection for they are not numbers used by Agassiz, the Smithsonian or any other source that I can run down. I can't find any previous record of any fishes from Chihuahua in Putnam's records or catalogues. Evidently these fish were specimens he found here since they are not on any of the lists of specimens received previous to 1861. There is no record of the collector or of the date of collection.

In his account of this species, listed as *Glaridichthys latidens,* Meek (1904, p. 134) wrote:

> I do not know this species, and I am inclined to think there is some mistake in the locality given for it. I do not believe this genus is represented in northern Mexico.

The genus *Poeciliopsis* is almost wholly restricted in its distribution to the Pacific drainage, where it ranges from Arizona to Colombia, although it is replaced by related genera in Panama and the adjacent part of Costa Rica. On the Atlantic slope it is not known north of the basin of the Rio Chachalacas, in Veracruz, Mexico (Plan del Rio; material at the University of Michigan), although the area between Veracruz and Chihuahua has been well explored ichthyologically. It is therefore natural that the designated locality of Chihuahua for *latidens* has been open to doubt. However, study of the drainage relationships shows that a considerable area in eastern and southeastern Chihuahua drains into the Pacific, chiefly through Rio Yaqui and Rio del Fuerte, but in small part also through Rio Sinaloa and Rio Culiacan. Since Meek (1904, p. xxxviii) collected in the headwater portion of the Yaqui and reported only *Poeciliopsis occidentalis* for that region, and since extensive collections made by Ralph G. Miller and John T. Greenbank and party in the middle and lower parts of the same river contain no species comparable to *P. latidens,* it is concluded that the types of that species were not collected in the Rio Yaqui system. If correctly referred to Chihuahua, they probably came from the upper part of the Rio del Fuerte although no collections are at hand from this section of the river. Lower in the same stream, in both Sonora and Sinaloa, a species we identify as *Poeciliopsis latidens* is common. This species also occurs in the Sinaloa and Culiacan systems, but it seems improbable that the types were taken in either, for the areas they drain in Chihuahua are small, sparse in population, relatively inaccessible and very probably too high and mountainous for this type of fish.

POECILIOPSIS LATIDENS (Garman)

Glaridodon latidens.—Garman, 1895, p. 42, Pl. V, Fig. 11, teeth (original description; Chihuahua, Mexico).

Glaridichthys latidens.—Meek, 1904, p. 134 (account taken from Garman; type locality questioned). Regan, 1906-08, p. 99 (account taken from Garman). Regan, 1913, p. 1002 (species listed without description).

Poeciliopsis latidens.—Hubbs, 1926, pp. 66-67 (comment on type locality; referred to *Poeciliopsis* on basis of description only). Jordan, Evermann & Clark, 1930, p. 189 (listed only). De Buen, 1947, p. 279 (provisionally listed; range given, obviously by presumption, as "Cuenca del río Bravo, en río Conchos (Chihuahua)"). Alvarez, 1950, p. 88, footnote (status not clear; unidentifiable from original description).

A critical study of the four types of this species demonstrates clearly that it is referable to the Poeciliidae, even though the type series includes no males. Each of the four females shows characteristics that separate the Poeciliidae from the other cyprinodont families. The first three rays of the anal fin are unbranched, the third ray reaches nearly to the tip of the fin, and the fourth ray is widely branched. The neuromasts or pit organs are arranged along the axial scale row posteriorly and, on the caudal peduncle, along the second row above the midventral row. The two series of scales with pit organs are separated, as in most poeciliids, by one row of unpored scales. Anteriorly, some neuromasts occur on scales in the next row above the axial series and in irregular locations above the anal fin and thence forward to below and behind the pectoral fin. The second scale row above the axial series may also have a few neuromasts near the dorsal fin (this is not a family character).

Although fully reliable generic identifications in the Poeciliidae can be made only from males, the general resemblance of the types of *Glaridodon latidens* to species of *Poeciliopsis* led the senior author to refer *latidens* correctly to that genus. This generic reference, however, would remain in doubt were it not for the remarkably close correspondence between the types of *latidens* and a *Poeciliopsis* that is common in northwestern Mexico (from near Alamos, Sonora, southward to Mazatlan, Sinaloa).[2] *P. latidens* is a banded or spotted species with the outer row of firm teeth arranged in a broad arc. Of the species heretofore referred to this genus, only *P. fasciata* (Meek), from the Pacific drainage of southern Mexico, fits this type, but the correspondence is not as close with *fasciata* as it is with the similar species in northwestern Mexico that we identify as *latidens*. The two forms are closely related but appear to be specifically distinct.

Description of the Four Types.—Fin rays: dorsal 7 and anal 9 in all (since Garman counted the two elements of the last ray separately, he reported 8 and 10 rays, respectively, for these fins); pectorals 12 or 13; pelvics 5 or 6; caudal 13 or 14 (11 or 12 branched) in 3, the counts questionable since the outer rays are broken. Scales in lateral series (from shoulder girdle to caudal base) 30. Vertebrae (including urostyle) $13 + 19 = 32$ in all (as determined by X-ray photography and further verified on the specimen dissected by Garman). Gillrakers (including all rudiments) on first arch 13 in 3 and 14 in one. Mandibular pores 2–2 in all; preopercular pores 7–7 in 2, the number indefinite in the remainder due to irregularities in the closing of the canal; pores on preorbital represented by an open groove; no pores on top of head, but there is a pair of more or less developed longitudinal grooves on the interorbital and a nearly transverse postorbital canal which may be open or roofed over, with a pore at either end.

The dentition, of major importance in the classification of the species of *Poeciliopsis*, is essentially as described and figured by Garman. The outer teeth are moderately long, and are hooked backward and semi-erect throughout. The outer edge of each tooth is moderately expanded toward the tip, the inner edge broadly expanded and more or less angulate, sometimes approaching a secondary cusp. As a result each tooth has a rather asymmetrical leaf shape. The outer teeth are rather firmly implanted, especially as compared with the loosely attached teeth of such species as *P. turrubarensis* (Meek) and *P. presidionis* (Jordan & Culver). These teeth form a rather strongly curved and very even series, without a median indentation. They are comparatively large and few (about 20 to 24 in lower jaw). The inner teeth form an irregular series that lies close to and parallels the outer row. The inner row forms an even arc that extends farther backward in each jaw than the outer row, in an almost longitudinal continuation of the sweeping curve. The inner teeth slightly approach the outer ones in individual form.

There are about 8 or 9 narrow, dark, transverse bars, counting a rather indefinite small one at the base of the caudal fin and a trace of another at the shoulder. The better-developed bars are somewhat higher than the length of the eye. The next to the last is about as well developed below as above the midline of the side or is even better developed below, but proceeding forward the bars are more dorsal and some of those on the trunk reach well toward and sometimes to the mid-dorsal line. There is a fine dotted axial streak that disappears near the head, a fine pencilled black streak between the anal and caudal fins, and a weak, deep-lying, irregular row of dots between the caudal and dorsal fins and before the dorsal, disappearing anteriorly. Near the back the surfaces of the scale pockets become rather thickly and evenly peppered with black dots and are bordered by broad crescents, but downward on the sides the crescents become narrower and less regular. Some melanophores extend downward to the anal fin, but the lower part of the peduncle (except for the streak) and most of the abdomen are largely devoid of melanin. Melanophores very weakly line the dorsal, caudal and anal rays. There are rows of scattered dots along the pectoral rays but apparently none along the pelvic rays. No definite spots or bars are evident on any of the fins, which were described by Garman only as "clouded with brownish." The whole top of the head is pigmented, with some intensification on the snout, especially in a large blotch before each nostril. The upper lip is dark. The chin, including the intergular region, is puncticulate; the preorbital largely so. A narrow band of pigment also borders the orbit posteriorly but fades out ventrally. The cheek has almost no pigment. The opercles are silvery, with very little black pigment except for a definite concentration on the upper anterior part.

The axis of the body is almost straight and the dorsal and ventral contours are about equally curved anteriorly (suggesting a midwater habitat). The origin of the dorsal fin lies a little in advance of or approximately over the end of the anal base, and before the base of the caudal a distance measuring 1.7 to 1.75 times in the predorsal length (stepped measurements are used throughout). The origin of the anal fin lies midway between the caudal base and the upper end of the preopercle. The distance from the tip of the snout to the insertion of the pelvic fin is contained 2.0 to 2.5 times in the standard length. The body cavity does not extend into the urosome.

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[2] Since this paper was put in type, specimens have been received that extend the range of *P. latidens* 35 miles farther south.

The greatest body depth is contained 4.3 to 4.7 times in the standard length. The depth is maintained through the caudal peduncle, the least depth of which enters the head 1.6 to 1.9 times (the long preservation and poor condition of the specimens has probably resulted, however, in a deepening of the peduncle). The length of the head enters the standard length 3.7 to 3.9 times. When stepped into the head length, the depth of the head measures 1.3 to 1.4; the width, 1.5 to 1.6; the interorbital width, 2.3 to 2.4; the distance between the orbits ventrally, 2.6 to 2.8; the length of the snout, 3.6 to 4.8; the diameter of the eye, 3.6 to 4.4; and the greatest overall width of the mouth, approximately 3.0.

In top view the mouth is moderately curved. The midline length of the upper lip is about one-fourth or one-fifth its greatest width. In side view the gape is moderately developed; the length in projection is about equal to the diameter of the pupil. The main part of the gape forms an angle of about 20° with the horizontal throughout about two-thirds of its length and then becomes nearly vertical. The length of the upper jaw enters the head length 3.3 to 3.4 times. In side view the angle of the head is 33° to 39°; that of the muzzle 89° to 90°; in front view, lines across the orbit meet below at 15° to 19°.

The depressed length of the rounded dorsal fin is contained 3.7 to 4.0 times in the predorsal length. The anal fin is also rounded and its length enters the distance from its origin to the caudal base 2.2 to 2.4 times. The length of the pectoral enters the head length 1.5 to 1.6 times. The short pelvic reaches to about the middle of the anus and its length is contained about 2.6 to 3.0 times in the head length. The pelvics are separated by a space nearly twice the width of the base of either fin.

Diagnostic Characters of Poeciliopsis latidens (Other Than Those of Gonopodium)

A small, banded and/or spotted species of *Poeciliopsis* with the outer teeth few, asymmetrical, rather long and firm, hooked backward, and semi-erect throughout, arranged in a broad and evenly curved arc, without median indentation. Each outer tooth has a rather asymmetrical leaf shape (Garman, 1895, Pl. V, Fig. 11). The inner teeth are irregularly arranged, usually in one series, in an even arc that parallels the outer row of teeth, but is continued farther back, almost longitudinally, in each jaw. In form the inner teeth slightly approach the outer ones. There are about 7 to 12 narrow, dark transverse bars and spots in adult females, most commonly 8 or 9 (all faint spots or bars were included in the count). Typically at least one, and usually several, of the bars reach or nearly reach the mid-dorsal line. The bars and spots are variable in shape and irregular in spacing, both individually and bilaterally. Typically, few bars extend much, if any, below the middle of the sides. In the adult males, the spots and bars are usually fewer than in the females, but are often more intense; they vary from about 6 to 10, typically 7 or 8. About 1 to 3 bars extend to or close to the mid-dorsal line. As in the females, few bars extend below the middle of the sides and their development and spacing is variable and asymmetrical. There is a definite though not pronounced dark streak on the anterior dorsal ray and first inter-radial membrane in each sex. In the immature fish the bars and spots are usually less numerous and the bars often extend below the midsides. The preorbital is naked. The pores of the lateral-line system on the head are arranged as follows: mandibular pores well developed, 2–2; preopercular pores variable, 5 to 7, typically 7–7; and preorbital pores varying from an open groove (0–0) to 3–3. The body axis is almost straight and the dorsal and ventral contours are about equally curved anteriorly.

Gonopodium of Poeciliopsis latidens

Value of Gonopodial Characters.—The pertinence of *Glaridodon latidens* to the genus *Poeciliopsis* is attested by the remarkably constant finer structure of the marvellously complex gonopodium (the anal fin of the male modified as an intromittent organ). Very minor differences come to light when the organ of *P. latidens* is compared in detail with that of *P. presidionis* (the type species) and other species referred to the genus, but many trenchant distinctions become apparent when the gonopodium of *P. latidens* is contrasted with that of the species classed in any other genus of the subfamily Poeciliopsinae (Hubbs, 1924, pp. 9-10; 1926, pp. 62-64; 1936, pp. 232-235). These conclusions would have been evident on the basis of the gonopodial characters described in 1936 and are definitely strengthened and extended by a survey of the male genitalial characters of the Poeciliopsinae recently made by the senior author. There is scarcely a part of the gonopodium that does not exhibit fundamental resemblances within the genus *Poeciliopsis*, and striking differences between the related genera.

In this as in other groups of the Poeciliidae, the gonopodial characters are of vastly greater taxonomic significance, above the species rank, than all other known morphological features combined. For these reasons, the description of the gonopodium needs to be long and detailed, merely to define characters by which other species and genera differ.

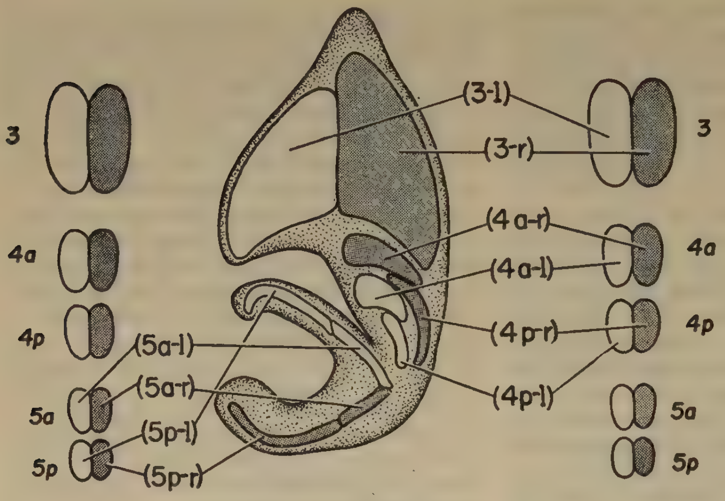
Methods of Study.—The gonopodial features are difficult to determine, because the rays are crowded and folded together, are in places bilaterally asymmetrical to a surprising and on first study confusing degree, and are highly modified, especially in the minute segments near the tips of rays 3 to 5. With repeated study and practice, however, the structures can be made out under appropriate lighting and magnification, particularly when the fin is manipulated with two fine needles. It is helpful, especially on early study, to tease (or chemically dissolve) the individual rays apart, or at least to unfold the fin or to pry the overlapping rays aside as the organ is turned, so that individual rays may then be followed. Toward the tip, where the segments become inordinately small, the manipulation entails great but, with care and patience, not insuperable difficulty. After the detailed structure is learned, the extreme constancy of the various parts can be perceived by gross examination and probing, without continued splitting apart of the rays. Earlier descriptions of the poeciliopsine gonopodia, such as those of Hubbs (1926), were crude and in some respects inaccurate, as was later pointed out (Hubbs, 1936).

Terminology.—In matters of orientation and terminology of parts we do not follow all the innovations made by Gordon & Rosen (1951) and Rosen & Gordon (1953). The gonopodium as a whole and its constituent rays are described as though held vertically downward from the base, as is customarily done in describing anal fins. Thus the front or anterior edge of the whole gonopodium or of any ray, in our terminology, is the morphological front part, not the lower or ventral part as usually described by Gordon & Rosen, who viewed the gonopodium as it is held at rest, extending almost straight backward. Similarly, we speak of the direction toward the tip of the fin as downward, not backward. The terminology of parts we follow agrees with the conventional illustration of the gonopodia in vertical position and avoids inconsistencies and awkward expressions. Similarly, we follow the primitive morphological orientation of rays that become rotated 90° or 180° in the elaboration of the gonopodium. In details, we retain the term *trough* rather than *canoe-like form* for the concave posterior edge of ray 5; *crescentic horn* for a structure curving over the extreme tips of the rays; and *membranous hood* for the dermal keel around the tip of the gonopodium. And we do not carry over from the nonhomologous condition in *Xiphophorus* the distinction between proximal and distal serrae (on ray 4p). We find it convenient to distinguish formally between the left and the right halves of given rays or branches of rays, for the two halves are often structurally different; thus, 3-l means the left side or segments of ray 3, and 4p-r means the right side or segments of the posterior branch of ray 4. Since the modification of the anal fin involves almost all its parts, the entire fin, beginning with rudimentary rays 1 and 2, is treated as the gonopodium. The last ray, as we consistently define it for the soft dorsal and anal fins, comprises the last two elements that are structurally distinct, including their structural bases, whether these elements be approximated or widely separated.

Description of Gonopodium.—The following description is based on the 57 males with completely or almost completely elaborated gonopodia in a large collection (UMMZ No. 164642) from Rio Yecorato, tributary of Rio Sinaloa, about 7 miles north of Guasave, Sinaloa, Mexico; collected by R. G. Miller on May 6, 1942.

The gonopodium is a very long and slender structure, inserted far forward (preanal length 43 to 48, averaging 46, percent of the standard length, in 30 specimens) but extending to within about an eye's length of the procurrent caudal rays. In the same specimens the overall length is 42 to 47 (average 45) percent of the standard length. The gonopodium is relatively thick (weakly compressed); near the middle of its length its left–right width is more than half the anteroposterior length.

The main rays (3 to 5) of the gonopodium are profoundly modified in size, shape, relative position and symmetry, as is indicated in part by the somewhat diagrammatic sketch (Text-fig. 1) representing the approximate appearance of a cross-section toward the middle of the length of the longest rays. The right side is weakly convex, the left side deeply concave, and ray 5 is rotated clockwise so that the tips of 3-l and 5p-l are almost in contact. As in all of the hundreds of specimens of *Poeciliopsis* examined, the tube is consistently on the left side. All 57 males in the series studied and 7 additional more or less completely transformed specimens have a sinistral gonopodium. This finding confirms the views of Hubbs (1936: 232-235) and of Hubbs & Hubbs (1945: 290-293), that the laterality of the gonopodium is consistently characteristic of the genus in all Poeciliopsinae (other than *Xenophallus*). The recent re-exam-



TEXT-FIG. 1. Semidiagrammatic cross-section of the gonopodium of *Poeciliopsis latidens*, toward the middle of the length of the longest rays, with the rays and their branches and bilateral halves identified and homologized with the corresponding parts of a more primitive gonopodium (diagrammed at either side).

ination of the gonopodia in the various genera of the family reveals no other exception to this rule.

The asymmetry of the organ is consistent also in the position of the first two rays and of the posterior rays (behind 5), as is described below, and involves the detailed flexure of the main rod (composed of rays 3, 4 and 5). As viewed toward its anterior edge this rod, consistently, is gently curved longitudinally toward its right side, with the strongest point of flexure about opposite the tip of ray 6. Beyond this point the gonopodium curves very gently toward the left side of the fish, outward to the moderately thickened and opaque area, about five-sixths of the way out, beyond which the terminal region, rapidly narrowing and becoming glassy, swings back toward or to the midline. The extreme tip is hooked almost at a right angle forward and slightly to the left.

When the undissected gonopodium is viewed from the right side, beyond the little distorted base and before the highly modified tip, there are visible: (a), the strongly curved right side of ray 3 (3-r), occupying about half the side; (b), the part of 4a-r that is not overlapped by the produced edge of 3-r; (c), almost all of 4p-r; then, (d), curving away, 5a-r, and, (e), when the troughlike ray 5 is rotated counterclockwise away from its normally infolded position, also 5p-r, curving away toward the left. When the gonopodium is viewed from the left, there are seen only: (a), the extreme front of 3-r; (b), the whole rounded left side of 3-l (narrower and with a less trenchant rim than the right side of 3-r); and (c), the morphologically right (but now actually left) side of 5p-l and 5a-l, plus (d), the sloping left side of 5a-r and, (e), the very edge of 5p-r; also (f), some of the left side of 5p-r, when the trough is rotated counterclockwise. When in normal position 5-l, rotated nearly 180°, fits against or close to the left edges of 4a-r, 4a-l, and 4p-l; and 5-r is rotated nearly 90°, in the same direction.

The gonopodium is heavily charged with black pigment along the right side of ray 3. The posterior part of this ray is clear, except very near the base and except on the outer third of the fin, out to the unpigmented vitreous tip. There is also a heavy suffusion of pigment along the trough of ray 5 and there are scattered dots on the right side of the main part of the gonopodium and along the short posterior rays.

Rays 1 and 2 are more minute than in most related forms. They are consistently deflected somewhat toward the left side and lie in a shallow trough between the basal forks of 3. Ray 2 overlaps at most one segment of 3 beyond the unsegmented base.

Each rather compressed fork in the hidden base of *ray 3* is broadly expanded at the extreme end, beyond which the fork is at first slender and then is dilated anteroposteriorly toward the union of the forks; the expansion continues toward the basal segments. The unsegmented base is long. The ray is only moderately expanded, less so than in most related forms, along the first few segments beyond the unsegmented base. These expanded segments are only about twice as broad as long. The basal sutures of 3-r run transversely near the posterior edge, but are deflected slightly downward toward the front edge. The first few segments of 3-l are separated by V-shaped incisions on the posterior margin. The longitudinal suture between 3-l and 3-r runs distinctly to the left side of the anterior crest of 3, farther to the left than in some other species of the genus. Throughout the length of ray 3 the sutures remain essentially transverse. Before the middle of the length of the ray, the segments change from broader than long to about square (as seen at right angles to the surface of the ray). Near the outer limit of the slight distal thickening, ray 3 narrows and in cross-section changes from a broad triangle to a relatively thin, weakly curved, transverse structure greatly narrowed in lateral view but only moderately constricted in anterior view. Beginning with a point where this transformation in form has become nearly completed, and extending outward for a distance about twice the length of one of the median segments of the ray, several segments are almost completely fused to form the *consolidated segments* characteristic of the genus. This structure is relatively soft. Beyond the consolidated segments, the sutures again become sharp and a few of the segments become subserrate on the right margin. These outer segments are somewhat wider than long but are not strikingly dilated (as they are in some species). Each segment-half (the two halves flare apart in one plane) is longer than wide. The extreme distalmost segments become greatly reduced, most notably in width. Somewhat longer than broad, they extend to the extreme hooked tip, on the inside of the curve.

Near the base *ray 4* is moderately thickened, more so on the anterior than on the posterior edge. The basal segments in side view are less than one-half broader than long. The left and right halves are in full and approximately symmetrical contact. At the very base ray 4 lies just behind 3, the two abutting without overlap, but soon 4 becomes displaced toward the right, so as to lie against 3-r and to be overlapped in part by the trenchant posterior edge of 3-r. Not far beyond the tip of 6, the ray branches to form 4a, which takes over the thickened portion and becomes rotated far toward the left, and 4p, which is somewhat broader in side view than 4a. Ray 4a becomes more nearly transverse than longitudinal, whereas 4p remains chiefly longitudinal. As a result the whole ray is very strongly curved. Its total anteroposterior width is much less than the width of the left side of 3. All parts of 4 are comparatively robust. In cross-section each half of 4p is a thin plate, gently concave on the left side and convex on the right. The left segments of each branch come to lie partly behind their right partners (as is particularly evident when the rays are manipulated with a needle), because the thickened anterior (now essentially left) edge of 4a-l lies behind 4a-r. In side view, both branches of 4-l are narrower than those of 4-r. The posterior (now largely right) edges of 4a-l and 4a-r somewhat overlap 4p-l and 4p-r, respectively. The segments of 4, like those of 3, remain essentially transverse. Out toward the modified tip, the segments of 4p become nearly twice as long as broad; those of 4a, at least twice as long as broad. In this region the segments of 4a are about as long as those of 3 and about one-fourth longer than those of 4p.

Opposite the consolidated segments of ray 3, *ray 4a* flattens out transversely so as to lie close against and directly behind the similarly flat and transverse part of 3, and its segments are similarly though less completely consolidated. As the consolidated segments are approached, 4a-l becomes rather narrow, less robust, and very much softer than 4a-r, which is here the principal element. Toward the extreme tip, the segments of 4a-r, separating 3 and 4a-l and remaining transverse, become somewhat dilated but remain less than twice as wide as long. Continually diminishing in size, the segments of 4a extend to the extreme tip, hooking around the curved tip of 3. In the terminal region of the gonopodium, 3 and 4a are so closely apposed and are so similar (and are so different from and so well separated from 4p) as to give the false impression that they are the anterior and posterior branches of the same ray.

In the thickened subterminal section of the gonopodium, the segments of *ray 4p* become transformed into serrae. Including two or three segments of transitional form, the serrae number about 17 on each side (left and right), and cover about one-fifth the total length of the gonopodium. All but the most basal serrae of 4p-r are like rose thorns, each arising from a base about twice as long as broad. Each thorn is directed essentially backward, with some angulation toward the left. The serrae of 4p-l, in contrast, are directed toward the left. The several distalmost serrae of 4p-l form thorns that are wider and more compressed than the opposite elements of 4p-r. The other serrae of 4p-l are strikingly unlike the thorns of 4p-r, being flat and more or less two-horned, or merely truncated. In this outstandingly peculiar bilateral asymmetry of the serrae of 4p, *Poeciliopsis latidens* agrees with other species of its genus but differs from those of related genera. The serrae extend to about opposite the end of the consolidated segments of 3 and 4a. The more basal and the more distal serrae of the two sides are readily separated by a fine needle, and those of each branch are very loosely articulated, but the more median ones are more firmly connected (bilaterally and longitudinally). Toward the tip, ray 4p swings onto the left side of the gonopodium. Beyond the serrae the segments become extremely minute but seem to continue onto at least the base of the abruptly curved extreme tip of the organ. Such features are seen only under high magnification, with the gonopodial tip turned at the most propitious angle.

At its extreme, essentially symmetrical base, *ray 5* is considerably strengthened, though much slenderer than it is farther out. Very near the base, the ray rotates toward the left so that only the anterior edge lies on the right side. Before the end of ray 6, the left edge has already become trenchant and turned clockwise nearly 180°. Here is seen the start of the trough that characterizes the species of *Poeciliopsis* and some of the related genera. This trough is formed by the flaring apart, to somewhat less than 90°, of the halves (5-l and 5-r) of the ray. In this trough, as already noted, 5-l normally lies against 4, with its tip close to the posterior edge of 3-l. Throughout most of the length of the gonopodium 5a-l and 5a-r remain connected only at their anterior edges, while 5p-l and 5p-r are widely separated. Consequently, the trough is floored by the two halves of 5a as well as 5p. The whole trough is capable of considerable rotation: it can be moved clockwise to nearly close the gonopodial tube, or counterclockwise, tending to restore the primitive linear sequence of the rays. Near the middle of the gonopodium and for some distance toward the base, the sides of the trough diverge at nearly a right angle, but both basad and apicad the halves approach one another to decrease the angle. Throughout most of the length of the ray the segments of both 5a and 5p are greatly compressed platelets. The relative shapes of these segments differ at different levels and on the two sides. Just beyond the tip of 6, the left side is much more expanded than the right. The posterior rim of 5p-r rather abruptly swings toward the left and somewhat forward, and the right side rapidly regains a width approximating that of the left. The proportionate width of the segments of the two branches is dissimilar, however, for 5a-l as seen from the trough is little wider than 5p, whereas 5p-r is about twice as wide as 5a-r. In cross-section 5a-r is scarcely curved. Near the middle of the gonopodium the segments of ray 5, considerably shorter than those of 3 or 4, differ in dimensions in the two branches and on the two sides: those of 5a average about one-fourth longer than those of 5p; those of 5a-l are about twice as long as broad, whereas those of 5a-r are about 2.5 times a long as broad; those of 5p-l average about one-half longer than broad, whereas those of 5p-r are approximately square. Throughout their lengths, from the extreme base to the tip, the sutures of both sides and of both branches remain essentially transverse, and the two free edges form a rather even line, unmodified in the direction of serrae, lobes, or other processes. Each edge, more particularly the left, is hooked inward.

The *outer segments of ray 5* are considerably modified. Opposite the most basal serrae of 4p, the squarish segments of 5a-l have become about three times as broad as the more rodlike and strongly curved elements of 5p-l, and the segments of 5a-r are also broader than those of 5p-r. Beyond the middle of the gonopodium the stiff free edge of 5-l remains trenchant and approximated to the left posterior edge of 3, whereas 5-r becomes narrower and softer. Opposite the basal serrae ray 5-r becomes membranous and seems to disappear, so that at the tip of the gonopodium only 5-l is recognizable. Here 5-l forms a thin keel along the side of 4, just in advance of 4p-l, which is similarly turned toward the left. Opposite the base of the consolidated segments (and opposite the place where the bicornute serrae of 4p-l change into flat thorns), the posterior edge of 5-l remains nearly straight while the anterior edge is sharply contracted, so as to decrease the width of 5-l abruptly and greatly. Opposite the distalmost serrae 5-l becomes an extremely fine and delicate double strand closely connected with the almost similarly reduced tip of 4p. Both tips run along the edge of a slightly expanded membrane that narrows down to the left edge of 4a, near the base of the apical hook. In some specimens, on close scrutiny, the now excessively attenuated strands may be followed, together, along the edge of the hook.

All segments in the *tip of the gonopodium* are relatively soft. The extreme tip is minutely hooked, forward and somewhat to the left, nearly to a right angle. Along the outer edge of the hook the apex bears a thin, evenly rounded *membranous hood* about one-third as wide as long (the length measured along the morphologically posterior but here transverse apex). The weak to obsolete crescentic horn runs in the base of the membranous hood along the outer curve of the terminal segments of 3 and 4, which reach to the extreme tip.

The *four posterior rays* of the gonopodium are extremely short. Of these only ray 6 is thickened. It is in a thick opaque fleshy mass that is deflected consistently onto the left side of 5. The swollen tip of 6 is rounded along the front edge, both transversely and longitudinally. It is somewhat more convex on its left than on its right side. The segments become fused in the outer two-thirds of the swollen area.

Rays 7 and 8 are also distinctively modified, but in a very different and peculiar way. Both remain very slender throughout, not developing swollen tips such as are characteristic of certain other genera of Poeciliopsinae (7 may be very slightly strengthened near its tip). Each is only incipiently branched at the tip. These rays originate apart, in normal file, but instead of remaining well separated throughout, as they do in the young males and in females of all ages, and as they do in the males of most poeciliids, they abruptly converge to become very closely approximated or in actual contact along the middle section of their lengths. Here ray 7 consistently lies more or less to the left of 8, giving rise to the false impression that these rays are the slightly dislocated left and right halves of a single ray. Distally the rays diverge rather widely. This peculiar condition of 7 and 8 is a consistent character of *P. latidens* and of the other species of *Poeciliopsis*. It holds for all 57 developed males in the series studied, with one abnormal exception. In this aberrant specimen, ray 6 is minute and clavate and is concealed in the inter-radial membrane just in advance of the base of 7. The latter ray has taken over the form of 6, presumably because the developmental field that normally affects 6 acted on 7, which in this specimen follows 5. In this aberrant gonopodium, 8 is less slender than usual and is well separated from 7 and from 9.

The fore and aft elements of *ray 9* are greatly reduced. In some specimens they are discernible with difficulty, even under high magnification and good illumination, but are probably never completely atrophied. They lie close together well behind 7 and 8, often in a more or less thickened and irregular little mass or lobe.

A small scaleless area surrounds the posterior end of the gonopodial base, but there is no naked groove behind the fin.

The multitudinous gonopodial characters described above are all definitive—of the subfamily, genus, or species. These observations confirm the opinion that no structure-complex in fishes is known to be more replete with characters than is the gonopodium.

COMPARISON BETWEEN GONOPODIA OF P. LATIDENS AND P. PRESIDIONIS

When the gonopodium of *Poeciliopsis latidens*, as described above, is compared in detail with that of topotypes of *Poecilia presidionis* Jordan & Culver, the type species of *Poeciliopsis*, a most remarkable agreement in fundamental structure is seen to prevail, from the first ray to the last and from the base of the fin to the highly modified tip. Many minor differences, however, appear, and are validated by studying series of specimens. These distinctions are mostly of degree and illustrate the range of differentiation to be found between well-defined species of the genus, all within the limits of a single highly distinctive general pattern.

Insertion of Gonopodium (measured from extreme base).—*P. latidens:* farther forward, preanal length 2.1 to 2.33 in standard length. *P. presidionis:* preanal length 2.0 to 2.1.

Length of Gonopodium (from origin at extreme base to farthest tip).—*P. latidens:* averaging longer, 2.1 to 2.4 in standard length. *P. presidionis:* 2.3 to 2.5.

General Dimensions of Gonopodium (near middle).—*P. latidens:* relatively thicker (left-right width more than half anteroposterior dimension). *P. presidionis:* more compressed (width less than half anteroposterior length).

First Few Segments of 3-r (beyond unsegmented base).—*P. latidens:* less expanded, about twice as broad as long, with sutures only slightly decurved forward and downward; without longitudinal depression. *P. presidionis:* more expanded, about thrice as broad as long, with sutures strongly oblique (forward and downward); depressed longitudinally to receive overlap of 4.

Longitudinal Suture between 3-l and 3-r.—*P. latidens:* displaced a little farther toward midline. *P. presidionis:* nearer front ridge.

Width of Ray 3 near Middle of Fin.—*P. latidens:* about half width of gonopodium at same level. *P. presidionis:* much less than half width of gonopodium.

Consolidated Segment of 3.—*P. latidens:* very soft, narrower, with both contours grading evenly into those of following rays. *P. presidionis:* stiff, broader, with keeled margin at left side abruptly constricted just before end (but right edge grading evenly into edge of following segments).

Segments of 3 beyond Consolidated Segment.—*P. latidens:* each segment-half (the two halves flaring apart in one plane) longer than wide; a few subserrate on the right margin. *P. presidionis:* each segment-half about as wide as long, rather irregular in form but not distinctly subserrate on right margin.

Basal Part of 4 (opposite middle part of 6).—*P. latidens:* scarcely dilated; segments nearly square, less than 1.5 times broader than long; abutting 3-r. *P. presidionis:* markedly dilated; segments about twice as broad as long; overlapping 3-r.

Ray 4 near Middle of Length.—*P. latidens:* 4a more nearly transverse than longitudinal; ray much more curved; its total anteroposterior width much less than width of left side of 3; all parts more robust; 4-l normally lying largely behind 4-r. *P. presidionis:* 4a more nearly longitudinal than transverse; ray much straighter; its total width about equal to width of left side

TABLE I. COMPARISON BETWEEN TWO SPECIES OF *Poeciliopsis* FROM MEXICO
Data for *P. latidens* based on many specimens from throughout its known range

Character	*P. fasciata*	*P. latidens*
Vertical bars	Fewer, narrower, less variable in number, none replaced by spots.	More numerous, broader, very variable in number, some or all nearly replaced by spots (occasionally obsolescent).
Lateral markings: In mature males	2 to 6, typically 3 to 5, bars[1], 50 percent or more extending well below midsides. Two or more bars usually meet or nearly meet at midline of back on each side.	5 to 12, usually 7 to 10, bars and spots (or spots alone), the bars rarely extending well below midsides. Usually at least one, occasionally two, bars meet at midline of back in well-barred populations.
In adult females	3 to 6, usually 4 or 5, bars[2]. At least one and usually two or more bars meet at mid-dorsal line on each side.	7 to 14, usually 8 to 12, bars and spots (or spots alone). Typically, one bar reaches to or nearly to mid-dorsal line on one side (in well-barred forms).
Front of dorsal fin	Typically with a jet-black streak on first two dorsal rays and inter-radial membranes; concentrated at base of fin as a black spot.	First ray and inter-radial membrane with a dark streak, not concentrated to form a spot; streak often very weak and pigment nearly absent on membrane in some populations.[3]
Front of anal fin: In mature males	Blackened at base of gonopodium; outer parts of rays 3 and 5 not notably darkened.	No black spot at base of gonopodium; outer parts of rays 3 and 5 conspicuously dusky.
In adult females	Typically with a black spot or dash.	A dark streak weakly developed or absent.[3]

[1] Based on 58 male subtopotypes (UMMZ No. 161517).
[2] Based on 23 female paratypes (CNHM No. 4716).
[3] Occasional individuals in some populations approach *fasciata* in this character.

del Fuerte 7 miles northeast of Alamos, Sonora (UMMZ No. 161554). About 25 collections of this species are deposited in the Museum of Zoology, University of Michigan, and others at the University of California (Los Angeles) have been studied.

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of 3; all parts more compressed and fragile; 4-l normally lying beside 4-r.

Broadest Subterminal Segment of 4a (about midway between consolidated segment and tip of ray).—*P. latidens:* definitely less than twice as broad as long. *P. presidionis:* twice or somewhat more than twice as broad as long.

Trough of 5, Basal to and near Middle of Gonopodium.—*P. latidens:* less flaring, the sides forming an angle of less than 90°. *P. presidionis:* usually flaring more than 90°.

Relative Widths of Segments of 5 (relative lengths in cross-section, as in Text-fig. 1).—*P. latidens:* 5a-l little wider than 5p-l as seen from trough; 5a-r about one-half width of 5p-r. *P. presidionis:* 5a-l about twice width of 5p-l; 5a-r and 5p-r subequal.

Curvature of 5a-r (in cross-section).—*P. latidens:* scarcely curved. *P. presidionis:* strongly curved.

Several Segments of 5a-l Basad from Consolidated Segment of 3.—*P. latidens:* With morphologically anterior edge (now posterior and flexed to the left) forming a straight line. *P. presidionis:* each segment with anterior (now posterior) edge produced toward left into a firm rounded lobe.

All Ray Tips.—*P. latidens:* very soft. *P. presidionis:* stiffer.

Extreme Flexed Tip of Gonopodium (twisted forward and to left).—*P. latidens:* curved nearly to right angle or hooked beyond a right angle. *P. presidionis:* not curved to a right angle.

Tips of Rays 3 and 4a in Flexed Tip of Gonopodium.—*P. latidens*: extending to extreme tip; inner edge of apical flexure not appearing keeled. *P. presidionis:* ending abruptly in terminal membrane well in advance of tip, usually not far beyond middle of final flexure, so that the hood seems to extend around tip onto inner side of curve.

Crescentic Horn (in flexed tip of gonopodium).—*P. latidens:* weak to obsolete, not extending to tips of rays 3 and 4a. *P. presidionis*: usually strong and conspicuous, occasionally rather weak; extending in a weak hook well beyond tips of rays 3 and 4a.

Comparison with Poeciliopsis fasciata

Poeciliopsis latidens is most closely related to *P. fasciata* (Meek), from which it differs primarily in coloration and in markings (Table I). The principal difference lies in the number and shape of the vertical bars, which show sexual dimorphism in each species. Mature males of *fasciata* typically have only 3 to 5 narrow, vertical bars, and the females usually have 4 to 5; the total variation is from 2 to 6. Mature males of *latidens* usually have 7 to 10 broader bars and spots (or spots only), and the females generally have 8 to 12 such markings; the total range is from 5 to 14.

There is considerable variation in the markings of *P. latidens*. For example, in a sample from the Rio Quelite, Sinaloa (UMMZ No. 160576), vertical bars are almost absent and there are fewer spots than usual, 5 to 9, usually 6 to 8, in females, 7 each in two males, and 5 only in one male. In a collection from the Rio Piaxtla (about 45 miles north of Mazatlan), the vertical bars are narrow as in *fasciata*, but there is no dark streak at the front of the dorsal fin and the bars are more numerous than they are in that species. The markings of *latidens* do not appear to be constant within a single stream system, but all samples examined (25) can be readily distinguished from *fasciata* on the basis of one or more of the characters listed in Table I, and on other less obvious but constant differences, chiefly of pigmentation.

There appears to be a broad gap in the ranges of the two species. *P. latidens* is not known south of Mazatlan[3] and *P. fasciata* has not been recorded north of the Isthmus of Tehuantepec. The known range of *latidens* is believed to represent the actual range reliably because the region south of Mazatlan has been visited by fish collectors and no species of *Poeciliopsis* corresponding to *latidens* has been obtained. On the other hand, the area immediately to the west of the basin of the Rio Tehuantepec (where *fasciata* lives) is little known and we have seen no collections between western Oaxaca and Acapulco, Guerrero. In the brackish lagoon about 10 miles north of that city (Laguna Coyuca, UMMZ No. 164689) there is a species of *Poeciliopsis* that is representative of (and perhaps identical with) *fasciata;* the same species also has been taken in Arroyo Nuxco, Guerrero (UMMZ No. 159896), about 60 miles northwest of Acapulco. It may eventually be found that *latidens* and *fasciata* are connected by a chain of intermediates in the area between Guerrero and Sinaloa. If so, the two forms, with, perhaps, some additional subspecies, mav be referred to a single species (*latidens*).

Range

As now delimited, *Poeciliopsis latidens* is known to occur in streams tributary to the Pacific from the basin of the Rio del Fuerte, along and near the boundaries of Sonora, Sinaloa and Chihuahua, southward to the Rio Quelite (north of Mazatlan) and, along the coast, to the bay at Mazatlan, Sinaloa—all in northwestern Mexico.[3] The northernmost locality from which we have seen specimens is a tributary of the Rio

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[3] See footnote on page 3.

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EXPLANATION OF THE PLATE

Plate I

Fig. 1. Adult males of two species of *Poeciliopsis.* Above: *P. latidens,* 21.2 mm standard length, from Rio Yecorato, Sinaloa, Mexico (UMMZ 164642). Below: *P. fasciata,* 22.2 mm long, from Rio Tehuantepec, Oaxaca, Mexico (UMMZ 161517).

Fig. 2. Adult females of two species of *Poeciliopsis.* Above: *P. latidens,* 28.5 mm long, same data as Fig. 1. Below: *P. fasciata,* 28.0 mm long, same data as Fig. 1.

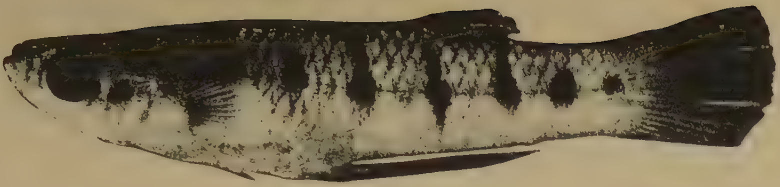

FIG. 1

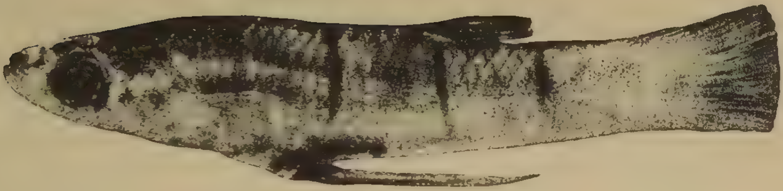

FIG. 2

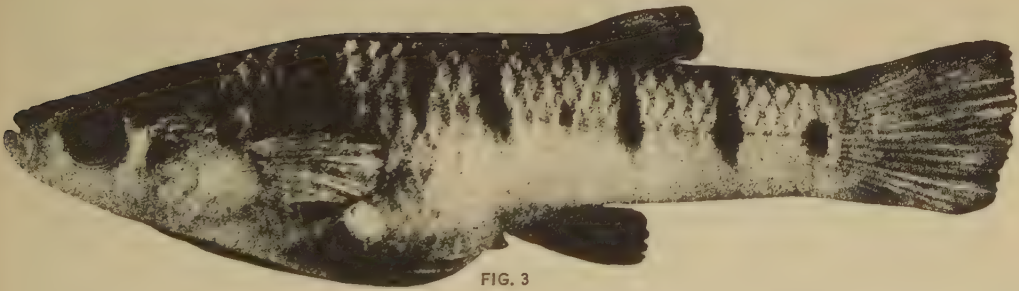

FIG. 3

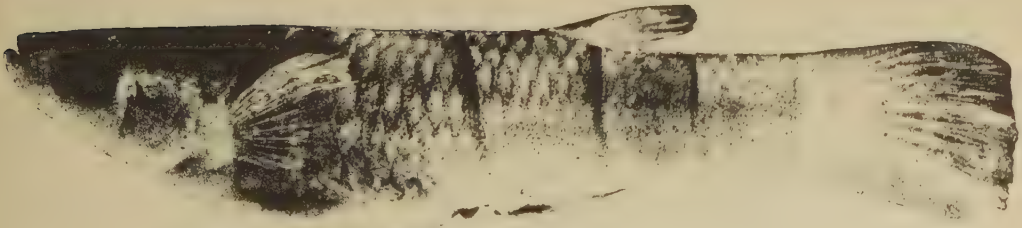

FIG. 4

GLARIDODON LATIDENS, FROM NORTHWESTERN MEXICO, REDESCRIBED AND REFERRED TO POECILIOPSIS

Under EXPLANATION OF THE PLATE opposite:
FIG. 1 refers to figs. 1 and 2 on this plate
FIG. 2 refers to figs. 3 and 4 on this plate

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A Problem in Oyster Taxonomy

JOEL W. HEDGPETH

IN THE past few years there has arisen a controversy over the proper generic name for that group of living oysters which includes such commercially important species as the American (or Virginia) and the Japanese (now Pacific) oyster. This controversy is the result of Lamarck's somewhat loose allocation of fossil and recent species to his genus *Gryphaea,* and the assumption by most of those involved in the present dispute that the living estuarine oysters cannot be included in the same genus as the Jurassic and Cretaceous Gryphaeas. Lamarck apparently saw no real generic difference between the ramshorn Gryphaeas and the modern species, as he included examples of both in his lists of species allocated to *Gryphaea.*

As a generic name for the Portuguese and related oysters, *Gryphaea* is a sentimental favorite among European oyster biologists (Vilela, 1951; Korringa, 1952); and Ranson, the leading oyster taxonomist, has pleaded for an exercise of the plenary powers of the International Commission to validate Lamarck's 1819 usage of *Gryphaea,* in which *angulata* is clearly the type, as opposed to the 1801 usage for which the Cretaceous *arcuata* has been subsequently designated as the genotype (see *Bull. Zool. Nomencl., 2:* 239-240, 4 May 1951).

This movement to deny the Cretaceous species the right to the name *Gryphaea* would, if successful, oblige paleontologists to use some such name as *Liogryphaea* (see Stenzel, 1947). Gunter (1950) seeking to avoid a suspension of the rules in favor of *Gryphaea* for the living oysters, proposes acceptance of *Crassostrea,* and several who work with living oysters have followed him in this usage (see, for example, Oyama, 1952). This is based on Gunter's feeling that "*Gryphaea* cannot be accepted for any living genera [sic] of oysters." In the light of one bit of suggestive evidence, this view may be untenable, and the whole problem of *Gryphaea* Lamarck 1801 versus *Gryphaea* Lamarck 1819 would consequently become academic. If we can demonstrate that *Gryphaea* is not an extinct genus, but is actually living today, and does indeed include the Portuguese-Virginia-Japanese complex, the European usage is correct for both living and fossil species and there is no problem of nomenclature *per se* involved. (The matter of *taxonomic convenience,* it should be understood, is laid aside in this discussion.)

Shell character in oysters is at best an incomplete criterion for the identification of species in oysters, and as Dechaseaux (1946) says (of *Liostrea*) specific determination "est très délicate et affaire d'appréciation personnelle." Nevertheless, the variations in shell structure in oysters have provided paleontologists with material for one of their classic studies in the variations of populations in successive strata. In this series of populations from the Jurassic beds of Europe, a successive series of overlapping populations with respect to the degree of curvature from a flat, oyster-like form to a true ramshorn *Gryphaea,* has been demonstrated (Fig. 1). According to Trueman (1922) such trends of variation have occurred several times during the Jurassic and Cretaceous, and the "Gryphaea" or end result of these trends is not a genus in the strict sense, but a form genus. Thus "Gryphaea" should properly be applied to only one of these end points, although it requires a very narrow conception of "genus" to assign the extremes of a continuous series of populations to different genera.[1]

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[1] "Nevertheless, the genus, though not a real entity, may be a real convenience; and

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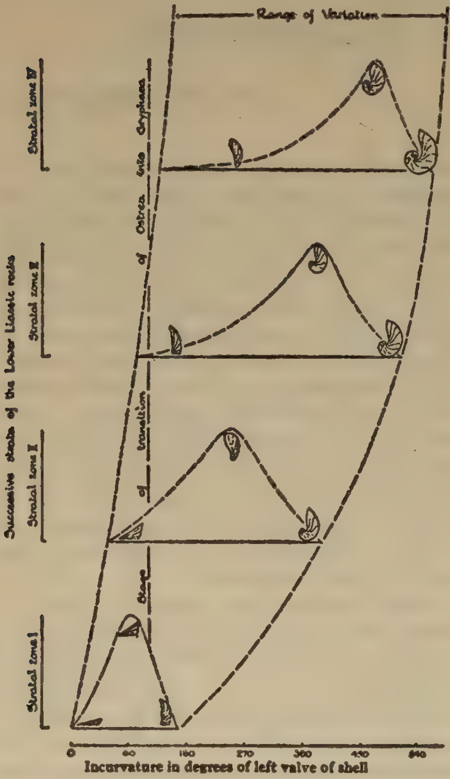

FIG. 1. Community evolution in Jurassic (Liassic) oysters. Progressive incurving of the shell is shown by the shifting peaks of the graphs; but each community contains forms having different degrees of incurvature. (After George, 1951.)

Simpson (1944) has considered the mannner in which such a conservative, slowly evolving stock as that of the oyster can persist through long periods of time, while giving rise to various offshoots:

> Most low-rate lines and, specifically, most or all bradytelic phyla seem to be highly and particularly adapted to some ecological position or zone with broad but rather rigid selective limits. They have few distinctive peculiarities that are not manifestly or probably adaptive . . . the adaptation does not necessarily involve loss of plasticity, and the low-rate line remains capable of throwing off branches that invade narrower or more fluctuating ecological niches and that evolve more rapidly in this new environment. . . . The bradytelic group remains and survives as an unprogressive nucleus of larger population, and the more rapidly evolving lines, more at the mercy of changing conditions, often become extinct.
>
> This relationship involves an equilibrium between tolerance and cyclic environmental change. At one end of the sequence are animals that tolerate almost no alteration of external conditions, but live in a virtually unvarying environmental niche, and at the other end are animals that tolerate extreme cyclic variations in temperature, salinity, and so forth, and live in environments characterized by such cycles. These periodically fluctuating environments must, however, be no less permanent, even though more variable, if bradytelic lines are to be found in them.[2] Thus, an animal that became adapted to continuous cold during the Pleistocene would either become extinct or rapidly evolve a different physiological adjustment in post-Pleistocene times. But an animal which developed wide temperature tolerance, which is no less an adaptation than is adjustment to a particular part of the temperature range, would tend to continue unchanged.
>
> . . . It is theoretically probable and it is consistent with observed facts that bradytely results from the equilibrium of large breeding populations of animals specifically adapted to a continuously available environment that is relatively invariable or has a rhythmic variation that corresponds with adaptive tolerance in the population. [Pp. 140–141.]

The ideas advanced by Simpson can be presented in the form of a diagram (Fig. 2), where the basic stock may be postulated as occupying the optimum, and the tachytelic lines as flourishing during the periods of extreme environmental fluctuation with a slow change in the optimum for the stock. In this connection, it is interesting to note the example of the *sellaeformis* stock of *Cubitostrea*, which Stenzel (1949) considers to have developed in marine rather than estuarine conditions. A similar saddle-shaped growth is described by Cox (1924) for the Miocene *Ostrea djuvanaensis*, incompletely developed specimens of which may be confused

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conventional definition may set objective limits to each genus as precise as those of a calendarial century or a statute mile." T. Neville George, 1951, p. 79.

[2] This is, in essence, a good description of the estuarine environment. (J.W.H.)

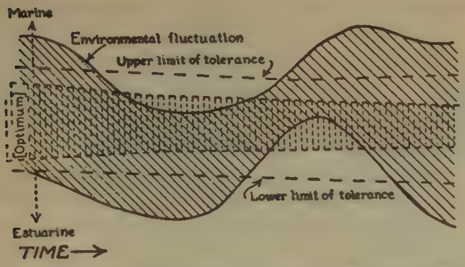

FIG. 2. Diagram illustrating environmental fluctuations in the estuarine environment.

with another species. The growth relationships of Stenzel's series, although expressed in a broadening of the hinge region rather than by curvature of the left valve, do not seem to be greatly different from those of the *Gryphaea* series (Fig. 3).

The living oysters of the complex with which we are concerned, however, are estuarine animals par excellence, whereas oysters of the *Ostrea* (*s.s.*) stock are less tolerant of the extremes encountered in estuaries, especially turbidity conditions, and are not found as far away from the sea as the *Gryphaea* or *"Crassostrea"* stock. In the estuarine oysters we have then a persistent basic stock in one of the most permanent of natural environments (in the sense of range of factors rather than location), and insofar as shell characters are concerned there is little apparent difference between Mesozoic and modern oysters, whatever generic names they may bear. Because of this range of variation in shell structure, there is little indication of progressive change in the stock as a whole, which is probably one of Ranson's

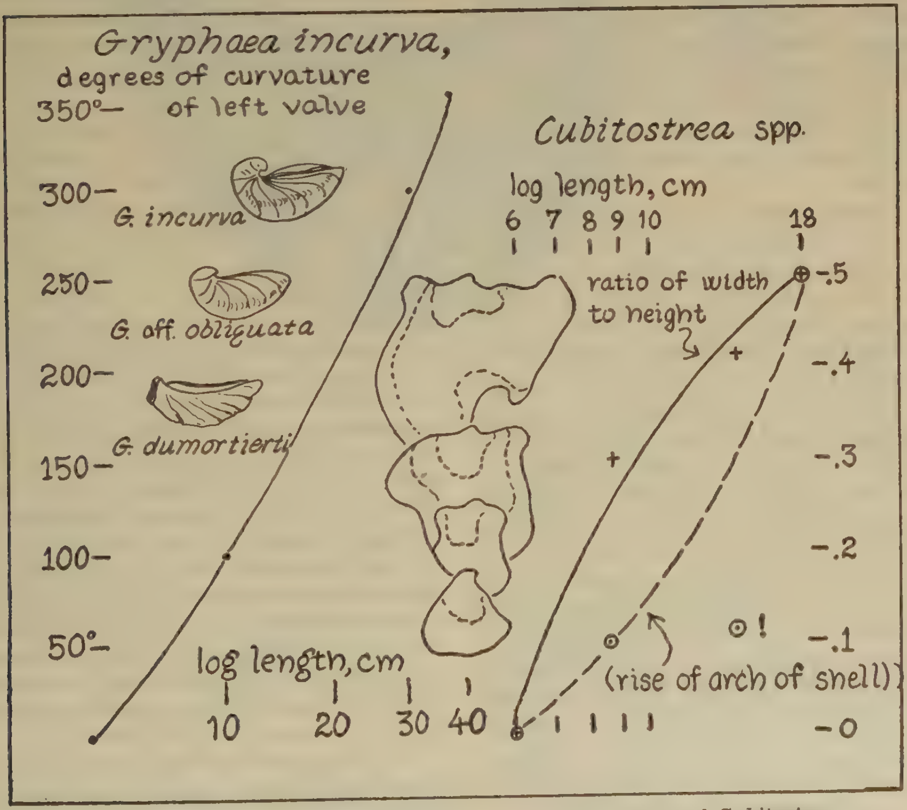

FIG. 3. Comparison of growth relationships in *Gryphaea* and *Cubitostrea*.

reasons for concluding that there has been no evolution in oysters since the close of the Mesozoic.

Ranson's ideas of evolution, as exemplified by oysters, are somewhat poetic. His idea is that the fauna as a whole is renewed by "mutation" during the transition between geological periods while the parent species disappear. This process is a world-wide one simultaneously induced by forces not yet understood, involving changes in the molecular nature of protoplasm rather than changes in the chromosomes. Such evolutionary processes are not observed during the ordinary periods, such as our own, when the mutations which do occur are infraspecific (Ranson, 1943, pp. 184–200.) This implies irrevocable changes in the make-up of the basic oyster stock with each geological period (the limits of which are somewhat artificially set by geologists) which do not agree with our concept of the environmental tolerances of oyster stocks, and Ranson seems to be aware of this when he suggests that the recent species are probably derived from Cretaceous estuarine species.

It seems much more reasonable to suppose that we have in oyster stocks, and in the estuarine stock in particular, a succession of populations in which the genetic building blocks may be rearranged in various patterns without undergoing irrevocable changes in the protoplasmic structure of the entire organism. This mechanism would account for the succession of *Gryphaea* lines observed in Jurassic beds, and the possible persistence of such genetic combinations (although at much lower frequencies) in our own time. A few years ago the specimen of the Japanese oyster illustrated in Figure 4 was found in Puget Sound.[3] This "Gryphaea" freak is apparently not a growth form induced by confinement in a fissure, as it has no attachment scars, but a freak induced by a disturbance at a much earlier stage of development. It suggests a "phenocopy" or growth form indistinguishable from a genetic expression, and the possibility that it may actually be a genetic expression cannot be dismissed.

It suggests, contrary to Ranson's idea, that there has not been an irrevocable change in the whole stock, but that the protoplasmic factors, whether somatic or genetic, which induced the *Gryphaea* lines, are still latent in the estuarine stock of oysters. If this suggestion is worth consideration, the real question is: why are such forms so rare at the present time? Perhaps they are not as rare as supposed, but simply have not been called to the attention of conchologists, and we may be on the threshold of a new outbreak of "Gryphaeas." If so, Japan would be the logical place to look for such trends, since it is probable that this specimen was transported as a juvenile from Japan as are most of the *gigas* cultured in American waters.

A similar case of recurrence in the Eocene of an "extinct" form in oysters was reported by Packard (1923). In this case the form was of the *Exogyra* type, that is, the lower valve was laterally curved. The Exogyras also died out in the Cretaceous, and seem to be more closely related to the *Ostrea* stock than to the *Gryphaea-Crassostrea* complex (see Jourdy, 1924, for a monograph on *Exogyra*). Packard referred his aberrant specimens to *Ostrea*, concluding that "oysters retained the tendency to develop twisted beaks even as late as the middle Eocene." According to Owen (1953) the principal difference between the form of *Gryphaea* and *Exogyra* is one of growth axes: in *Gryphaea* the growth of the flat or upper valve is due "almost entirely" to the radial component, whereas in the concave valve growth is the resultant of radial and transverse components; in *Exogyra* growth is modified by a tangential component.

If nothing else, these examples emphasize the subjective nature of generic allocations in oysters, and the names we

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[3] The author is indebted to Dr. Myra Keen for calling his attention to this specimen and for the photographs.

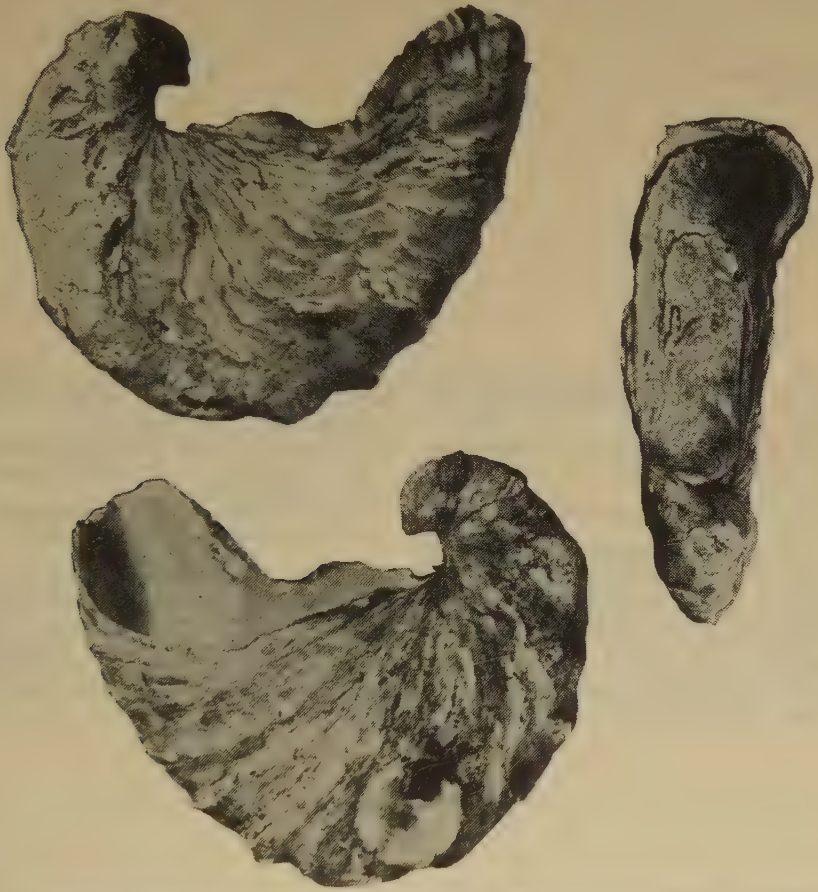

FIG. 4. Photographs of *"Gryphaea" gigas*. Slightly less than natural size. Stanford Univ. Paleo. Type Coll. No. 8111. Courtesy Myra Keen.

choose to apply to our modern stocks of oysters may be more a matter of taste (and predisposition) than a reflection of the genetic circumstances. To retain the name *Gryphaea* in both of Lamarck's usages would at least emphasize the essential continuity of this basic stock, and the evidence of such examples as *Lingula*, *Latimeria* (and its recently discovered relative), and Xiphosura indicates that such persistence is not impossible.

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683

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12

The Earth beneath the Sea—Geophysical Exploration under the Ocean*

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12.1 Introduction

Why are there continents and oceans? Have the deep-sea basins existed throughout geologic time with about their present shape and dimensions? Or have the continents and oceans gradually evolved over the past 3 billion years?

These questions are fundamental to an understanding of the origin and geologic history of the earth. They have not been satisfactorily answered. A description of the "first-order" features of the earth underneath the oceans must necessarily precede any attempt to answer them. The results from recent deep-sea exploring expeditions have made it clear that only five years ago our picture of these principal features was completely inadequate.

In the past, geologists comforted themselves with the belief that the sea was much more stable than the land, that little of geologic interest had happened there, that the broad expanses of the ocean floor were a monotonously uniform sea of mud over great distances, and that little could be learned about the earth's history from studies of the ocean. But they are now finding that the oceans have been the scene of intense and varied earth activity during the relatively recent geologic past, that the shape and structure of the sea floor are remarkably complex, and

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that within the upper layers of deep-sea sediments we have an unrivaled archive containing detailed records of climatic conditions during the last few million years.

The task of the geophysicist is not only to describe systematically what actually exists in the earth but also to determine why things are the way they are. He is concerned with the internal forces which have shaped the earth and which continually evidence their presence through earthquakes and volcanoes. These forces are surprisingly small. Table 12.1 compares the energy flux from within the earth with the average amount of energy received at the sea surface from the sun and the amounts utilized by plants and by our industrial civilization. It will be seen that the total flow of energy from within the earth is about 7000 times smaller in any given time interval than the energy received from the sun and about one-seventh of the energy utilized by land and marine plants in photosynthesis.

Table 12.1 Energy Flux from within the Earth

	10^9 ergs/yr/cm^2	10^{27} ergs/yr per entire earth
Heat conduction	1.6	8
Earthquakes	0.24	1.2
Volcanoes	0.008	0.04
Solar radiation	13,000	65,000
Photosynthesis	12	60
Human and industrial power	0.1	0.5

The seagoing scientist labors under several disadvantages: First is the great disproportion between the area to be covered—almost three-quarters of the earth's surface—and the tiny number of scientists working on problems of the sea. Geologists frequently deplore the gross inadequacy of geologic mapping on land; yet the area of the world ocean is nearly three times that of the continental areas, while the ratio of professional oceanographers to geologists is roughly 1 to 20. Second is the great expense and difficulty of work at sea as compared to its immediate practical rewards—the fact that man is a land mammal will be enthusiastically confirmed by any one who has been seasick in the small, oily, and uncomfortable craft which are utilized as research laboratories by oceanographers. In this harsh environment the oceanographer must be as much seaman as scientist, and his instruments tend to be rugged and crude with attendant loss of precision and flexibility. Third is the stubborn opacity of the ocean to visible light—this has produced the paradox that we actually know more about the surface of the moon than about the topography of the ocean floor. The submarine geophysicist must probe blindly into the depths and can visualize only indirectly the performance of his instruments and the processes which he is investigating. Fourth, for the most part he must make measurements, at a series of discrete points in space and time, of parameters which vary widely and often unpredictably from point to point and from time to time. Finally the geophysicist is largely denied the benefits of controlled experiment, that peerless tool of the laboratory scientist. The ocean and the solid earth cannot be controlled. The forces involved are too large and the time scale too great. The methods of the geophysicist must be akin to those of the detective who patiently pieces together all possible clues in his attempt to reconstruct what has happened.

Surprisingly enough, however, many kinds of geophysical work at sea can be conducted with relative ease compared with corresponding investigations on land. In seismic work, consistent signals can be obtained through the sea floor out to distances of 60 miles with an 80-lb charge, and on occasion records up to 100 miles are obtained. On land, a distance of 10 miles with an 80-lb charge is considered very good. Measurements of heat flow through the sea floor, although somewhat difficult experimentally, are straightforward in interpretation because of the relatively uniform and constant temperature of the bottom waters over large areas of the oceans. In contrast, it is extremely difficult to obtain unequivocal determinations of heat flow on land because of migrating ground waters, uncertainties introduced by the circulation of drilling fluid in wells, and changing atmospheric temperatures. In magnetic and gravity measurements, the ability to use the sea surface as a reference plane and the simultaneous recording of a bottom depth profile considerably facilitate interpretation.

Moreover, experimentation does have its place in submarine geophysical investigations, particularly model experiments in which oceanic processes are studied on a reduced scale, and the conditions are varied, one by one, to establish a framework of analogy by which the full-scale phenomenon may be better understood. For example, many people now believe that sediment-laden waters flowing down submarine slopes have played a major part in the transportation of sediments and may have brought about the cutting of submarine canyons. Yet no one has observed such currents in the sea. Their existence has been deduced from model experiments in the laboratory and by analogy with somewhat similar phenomena in lakes and in the atmosphere, *e.g.*, dust storms.

From its beginning 75 years ago in the great British *Challenger* expedition the scientific exploration of the deep sea has tended to run in cycles. Each cycle of exploration was initiated not only by the conceptual growth of new questions that men asked about the sea but also by the development of new techniques of exploration. Nearly all these techniques can be characterized as means for extending the personality of the scientist into regions that he can never see. The scientific explorer of the earth beneath the oceans must rely on observations at a distance. He probes into the dark with long fingers of steel, or listens for sounds made far away, or studies other phenomena that reflect the invisible character of the buried rocks.

Among the new tools of geophysical exploration developed in recent years are echo sounding, underwater photography, bottom coring and dredging, seismic refraction and reflection methods, devices for measurement of heat flow from the interior of the earth through the sea floor, means for measurement of the acceleration of gravity, and continuous-recording magnetometers which can be towed from ship or plane. Some of these new methods and the results obtained will be discussed in the remaining part of this chapter.

12.2 Echo Sounding and Submarine Topography

In the 50 years before 1925, a great deal of time and effort was spent in making soundings of the ocean floor with lead and line. But the number of soundings was so small and the locations of the points of observation so uncertain that only the barest outlines of the shapes of the sea basins could be discerned. With the development of echo sounding—depth determination by accurate measurement of the time required for a sharp pulse of sound to travel from an observing ship down to the bottom and back again—the true shape of the sea bottom is being disclosed at a rate undreamed of 25 years ago. This development has been accompanied by a great improvement in means of navigation in waters within 200 miles of shore, so that it is now possible to make topographic maps of the border areas of the oceans which approach in accuracy topographic maps of land areas. There has been much less improvement in navigational methods far from land, but even here the speed with which echo soundings can be taken has made it possible to construct maps of considerable areas that represent rather well the shape of the sea floor, even though the absolute location of the surveyed area is only approximate.

Although new discoveries about the topography of the sea floor are continually being made, some of the characteristic features are already clear. In the first place there is a relatively sharp boundary between the continental blocks and the ocean basins. This boundary zone is characterized by broad shallow shelves, probably cut by wave erosion during the glacial epoch, which break sharply at their outer margins into the continental slopes. These slopes, though rough in detail, are gentle over all, descending downward into the abyss at an angle of about 5°.

At many places throughout the world, steep and deep submarine canyons, often with rocky walls, are cut in the slopes and shelves.

Perhaps the most remarkable characteristic of the boundary zone is the very fact that it exists—that the continents are present as great islands of relatively light rock floating in the denser material of the sea floor and that there is a sharp boundary between these continental rafts and the abyss of the deep sea.

Beyond the boundary zone each deep-sea basin has a group of characteristic features. Here we shall confine ourselves to the Pacific Ocean. In its broadest aspects the Pacific can be divided geologically into two regions, a central basin and a surrounding marginal zone. The line of separation between the two is called the *andesite line* (Fig. 12.1). Its western limb extends south of and parallel to the Aleutian and Kurile Islands, thence east of Japan and the Marianas Islands, south through the Carolines, southeast to a point north of the Santa Cruz Islands, east of the Tonga Islands and south past the Kermadec Islands and New Zealand, probably to Antarctica. In the eastern Pacific the position of the eastern limb of the andesite line is not clearly delineated, but it undoubtedly lies east of the Galápagos Islands and perhaps west of Easter Island, thence southward toward Antarctica. North of the Galápagos Islands it approaches the continental platform of Central and North America. Within the andesite line the igneous rocks of islands are principally olivine basalt, and we may consider this region as the true Pacific basin. Outside the andesite line, the igneous rocks of islands are relatively high in silica and alumina. In the South Pacific approximately at 20° south latitude, the western and eastern segments of the andesite line approach within 3500 miles of each other. To the west lies the island-studded area with average depths of about 1600 fathoms which has sometimes been called the Melanesian subcontinent. To the east lies the equally shallow Easter Island rise. Rocks of andesite composition occur on Easter Island and on the islands of Melanesia.

The deep Pacific basin inside the andesite line is pimpled with sea mounts, many of which have a rough and irregular shape and are undoubtedly active or extinct volcanoes. In the North Pacific some of these sea mounts, with summit depths of 2000 to 6000 ft below present sea level, are nearly flat on top over distances of 2 to 20 miles (Fig. 12.2) as if their summits had been cut by a gigantic plane (Hess, 1946).* Fossil remains of clams, corals, sea urchins, and other animals which once lived in shallow water have been collected from some of these flat summits (Hamilton, 1953), and it is evident that the sea mounts were once islands which rose above the sea and were cut off by wave erosion. Their subsequent relative subsidence was caused either by a rise in sea level or a drop in the sea floor. On some of these drowned islands, coral reefs built upward at the same rate as the foundation subsided, and these became coral atolls. On others, for reasons unknown, the coral either could not get started or failed to keep up with the relative subsidence, and these became flat-topped sea mounts. Sea mounts with flat summits have not yet been found in the South Pacific, but numerous atolls occur there, and the combination of evidence from seismic, magnetic, and topographic surveys on the Scripps Institution of Oceanography *Capricorn* Expedition of 1953 indicates that several thousand feet of

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* Corresponding bibliographic references appear at the end of the chapter.

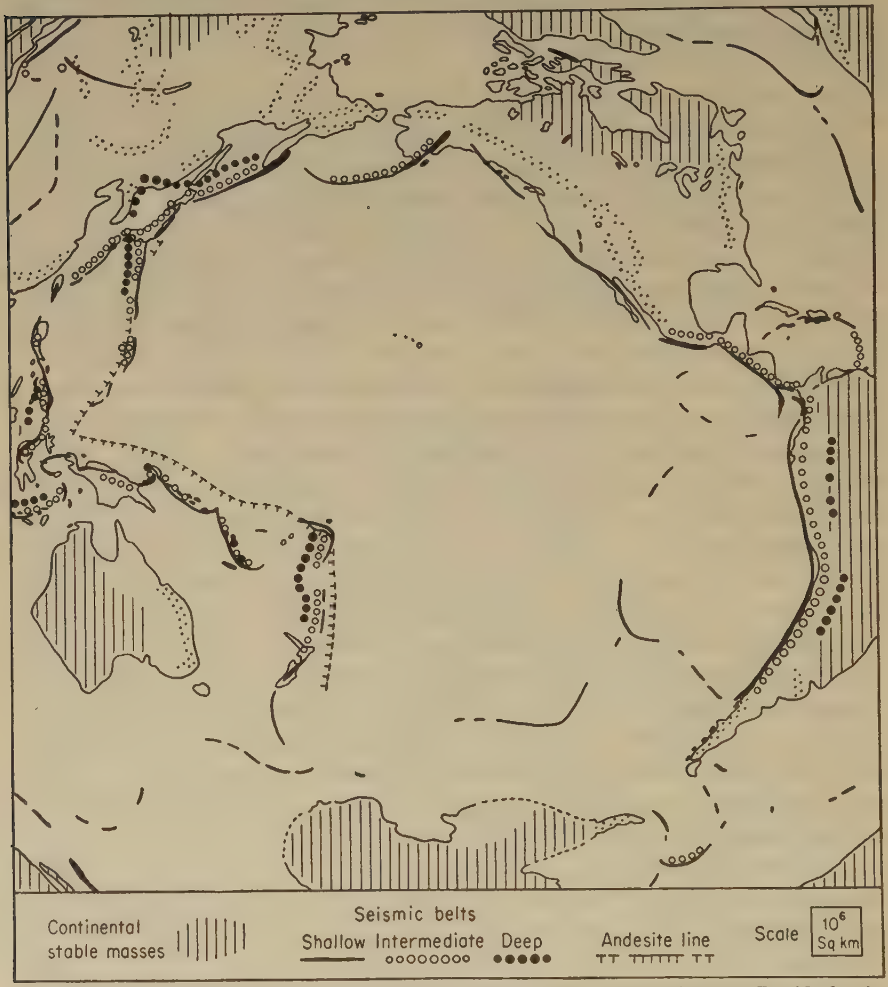

Continental stable masses
Seismic belts
Shallow
Intermediate
Deep
Andesite line
Scale
10^6 Sq km

Fig. 12.1 Approximate position of the andesite line separating the true Pacific basin from the marginal areas. (*After Gutenberg*, 1951.)

coral limestones rest on foundations of volcanic rock and that there has been a relative subsidence of the old volcanoes by at least several thousand feet. Fossils collected from North Pacific sea mounts and from boreholes in Bikini (Ladd, Tracey, and Lill, 1948) and Eniwetok Atolls (Ladd, personal communication) show conclusively that the subsidence has taken place within the last 100 million years, about one-fortieth of geologic time.

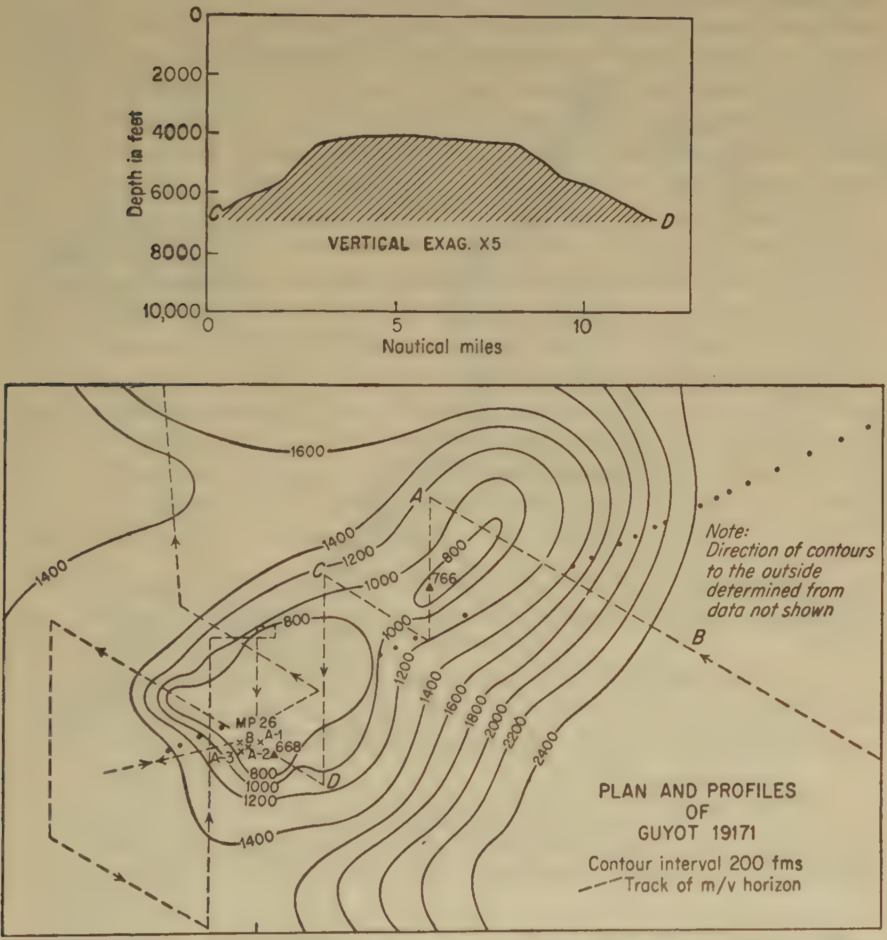

Depth in feet
0
2000
4000
6000
8000
10,000
C
D
VERTICAL EXAG. X5
0
5
10
Nautical miles
1600
1400
1400
1200
1000
800
766
A
C
B
D
800
1000
1200
1400
1600
1800
2000
2200
2400
MP 26
B
A-1
A-2
A-3
668
800
1000
1200
1400
Note: Direction of contours to the outside determined from data not shown
PLAN AND PROFILES OF GUYOT 19171
Contour interval 200 fms
Track of m/v horizon

Fig. 12.2 Plan and profile of a flat-topped sea mount in the central Pacific. (*After Hamilton*, 1953.)

One outstanding feature of the deep central basin of the Pacific is the relative absence of submerged mountain ranges which originated in folding or bending of the suboceanic rocks. For example, such island groups as the Cook, Society, and Marquesas Islands appear to rise as chains of volcanoes directly from the deep-sea floor rather than as peaks on a broad arch or swell (*Capricorn*, 1953). However, such a broad submerged structure is characteristic of the Hawaiian Islands and the Mid-Pacific Mountains in the North Pacific. In the South Pacific an uplifted fault block apparently underlies the atolls of the Tuamotus.

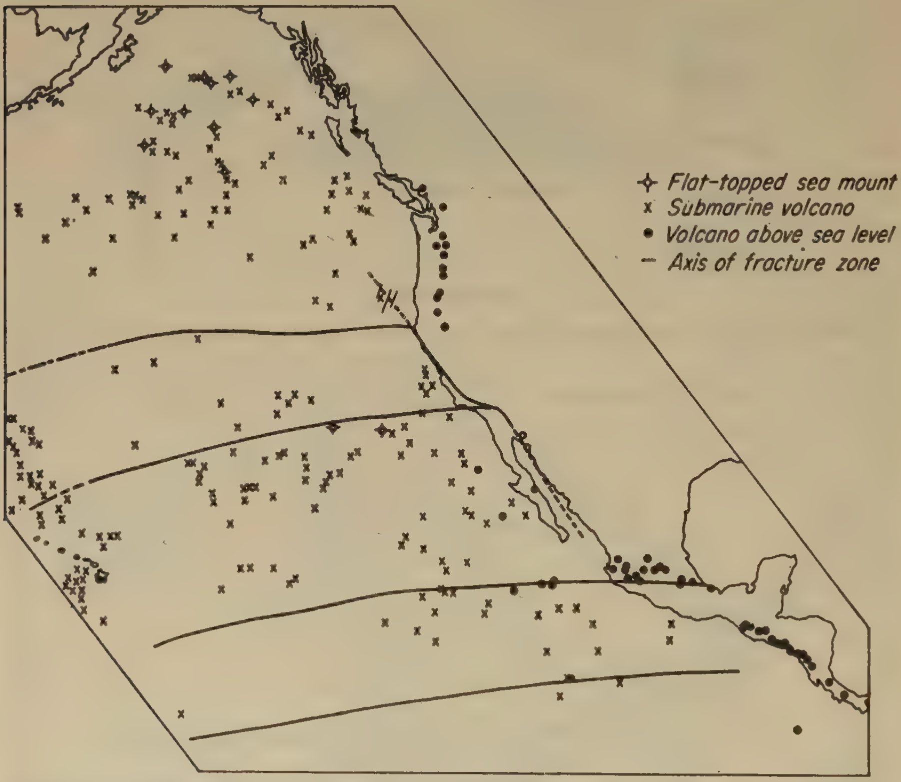


Fig. 12.3 Fracture zones, volcanoes, and flat-topped sea mounts in the northeastern Pacific. (*From Menard*, 1953.)

Major zones of fracture are found. Menard (1953) has recently shown that four straight and nearly parallel fractures at least 1500 miles long occur in the northeast Pacific (Fig. 12.3). These originate on the west coast of North America and extend westward as zones of long and narrow ridges, troughs, and escarpments. Each pair of fracture zones appears to bound a distinctive topographic province on the sea floor with characteristic average depth, degree of roughness, and shape of smaller topographic forms. For example, between the Murray escarpment, which extends westward from Point Conception, and the Clarion fracture zone extending westward from the Revillagigedo Islands there is an unusually large number of sea mounts (estimated at more than 2000). Few, if any, of these are flat-topped. One may argue, by analogy with experiments on the fractures of variously shaped bodies under stress, that these quasi-parallel fracture zones are the result of a single planetary stress system. If they are, they do not correspond as far as we know to any stress system that has been proposed in the literature.

The characteristic topography of the so-called subcontinental areas outside the andesite line differs in many respects from that in the deep Pacific basin. For the most part these regions are a mile shallower than the central ocean area inside the andesite line, but they contain deep, flat-bottomed, relatively steep-sided isolated basins, such as the Fiji and Philippine basins. Elsewhere in the subcontinental areas, the topography is much rougher and more complex than within the andesite line.

A characteristic feature of the boundary zone along the andesite line is the existence of long, excessively deep, V-shaped trenches. Examples are the Aleutian, Japan, Marianas, Kermadec, and Tonga trenches. Each of these trenches is part of a deep reaching structure characterized by contemporary and extinct vulcanism, large gravity anomalies, and a very high seismic activity. A typical section across the Tonga trench from west to east may be used as an illustration (Fig. 12.4). We observe the following features (not all shown in the figure):

a. *Melanesian subcontinent* at a depth of 1000 to 1500 fathoms
b. *Volcanic ridge* rising to about 700 fathoms capped by volcanic islands and sea mounts
c. *Tofua trough* with a maximum depth of about 1000 fathoms
d. *Main island ridge* reaching up to 30 to 50 fathoms, from which the elevated limestone islands of the eastern Tonga Archipelago rise to heights of 100 to 600 ft
e. *Tonga trench*, extending to depths of more than 5000 fathoms
f. *East ridge*, rising about 200 fathoms above the
g. *Pacific basin* to the east, with an average depth of 3000 to 2500 fathoms

The very existence of this giant structure is a riddle. What implacable forces deep within the earth could have caused such a large-scale distortion of the sea floor? Did the trench form long ago and is it now gradually being filled up with sediments, or is it still being formed so that at some future time it may be even deeper than it is today? What has become of the material excavated from the trench? How can we explain its location, close to an island chain and along the boundary between the 3-mile-deep basin of the Pacific with its black and heavy rock floor and the shallower island-studded waters of the southwestern Pacific? Why is it so narrow, so long, and so straight?

Seismic surveys by R. W. Raitt indicate a thin oceanic type of crust beneath the sea floor on both sides of the trench. Beneath the trench the crust is significantly thicker than on the two sides, the Mohorovičić discontinuity lying at depths of at least 15 and perhaps 20 km. It seems evident from the narrow V-shaped profile, irregular rocky surface, thin veneer of sediments, frequency of earthquakes, and existence of large anomalies in the earth's gravitational field that active movements of the crust are taking place on a grand scale at the present time along the axis of the trench. Farther west along the line of volcanic islands, events of equal violence but of greatly different character are occurring.

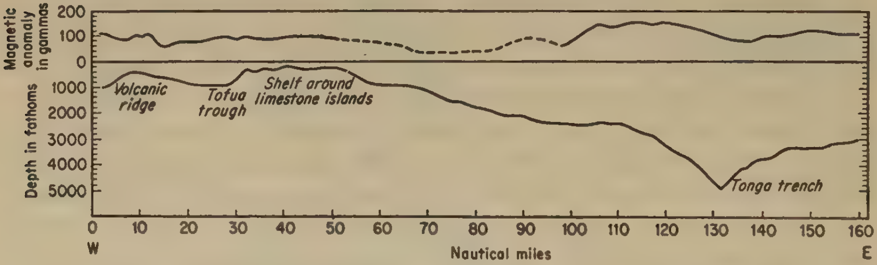


Fig. 12.4 Depth profile across the Tonga area. (*From Capricorn*, 1953.)

Along the trench every indication points to a squeezing together and downward bending of the earth's crust. In the volcanic region to the west, the rocks below the surface have melted and forced their way upward through the crust, perhaps because of relief of pressure at depth. One may reasonably inquire as to what has happened to the volume of rock which formerly occupied the space now filled with water in the trench. It is interesting to compare this volume with that of the material thrown out of the volcanoes. A rough computation, based on the thickness of volcanic sediments in the Tofua trough as found by the seismic refraction method, shows that these volumes are approximately equal. This does not imply that the material which was formerly in the trench has been turned into ash and cinders and vomited up on the sea floor by the volcanoes, but it may indicate that the material forced downward and perhaps westward from underneath the trench has filled at depth the space vacated by volcanic material thrown upon the sea floor.

One other computation is of interest: the heat per unit area and time released by this volcanic activity, supposing it has extended over 10 million years, is approximately equal to the average heat flow by conduction through the continents and through the sea floor. These two types of release of heat must be additive. Thus we have in this region much more energy flux through the earth's surface than over most of the earth.

12.3 Seismic Methods of Exploring the Crust and Mantle

It is not necessary to go to sea in order to explore the deep ocean. Gutenberg (1951), Wilson and Baykal (1948), Ewing and Press (1950), Stoneley (1948), and their collaborators have demonstrated the value, for determining suboceanic structures, of the study of earthquake records in which the vibrations have traversed paths underneath the ocean.

When an earthquake or other shock occurs in the earth, elastic waves proceed out in all directions from the point of origin and can be recorded by seismographs. Within the crust and mantle two types of waves exist —*compressional* or *P waves* in which the displacement is in the direction of propagation and *shear* or *S waves* in which the displacement is transverse to the direction of propagation. The velocities for the P and S waves are

$$V_P = \sqrt{\frac{k + 4\mu/3}{\rho}} \qquad V_S = \sqrt{\frac{\mu}{\rho}}$$

where k is the bulk modulus (the reciprocal of the compressibility), μ is the rigidity, and ρ is the density. The ratio of the two velocities is

$$\frac{V_P}{V_S} = \sqrt{\frac{2(1 - \sigma)}{1 - 2\sigma}}$$

where σ is Poisson's ratio. The velocities of both the P and S waves vary widely with the nature of the rocks through which they are traveling. Some typical values of V_P based on laboratory measurements are given in Table 12.2. Thus by measuring the travel times of compressional and shear waves from earthquakes (or large explosions) of known position to a receiving station, the elastic constants of the rocks through which the waves have passed and the geometrical configuration of the rocks can be determined; these in turn lead to a basic understanding of the geologic features. A summary of results from studies of nearby earthquakes and explosions in Europe, North America, and Africa concerning seismic velocity and thickness of the components of the earth's outer shell, called the crust, has been prepared by Bullard (1953). In most of these continental cases, velocities between 5.5 and 6.35 km/sec are found beneath a superficial layer of sedimentary rock. These are believed to represent a zone of plutonic "acid" igneous rock (called "granite" by the seismologists) at least 10 km thick. Beneath the "granite" there is evidence that a zone with velocities between 6.5 and 7.1 km/sec exists, but this is not found in all cases. At the bottom of the crust, the observed velocities increase sharply; this break is called the *Mohorovičić discontinuity* after its discoverer, and it occurs at depths under the continents of 27 to 47 km. As will be shown below, these inferences from seismic data on the structure and thickness of the crust under the continents are in marked contrast to the seismic results on the character of the crust under the oceans. The most convincing results under the oceans have been obtained from studies of the surface waves of earthquakes and by seismic refraction and reflection measurements on shipboard, using explosive sources.

Table 12.2 Velocities of Compressional Waves, Km/Sec

Material	At normal temperature and pressure	15 km below surface
Sand	0.2–2	
Alluvium	0.5–2	
Sea water	1.5	
Clay	1–2.8	
Sandstone	1.4–4.3	
Shale and slate	2.3–4.7	
Limestone	1.7–6.4	
Gneiss and schist	3.1–5.4	
Granite	5.2–5.6	6.1
Basalt	5.1–5.6	
Dunite	....	7.8

Although surface waves are more conspicuous features on most seismograms than the above-described body waves, their study has not received great emphasis, so that at present there are many unexplained or partially understood surface-wave arrivals. Elastic theory provides in general for two types of waves at the surface of a solid, commonly called *Love* and *Rayleigh* waves after their discoverers. Love waves are shear waves polarized horizontally. They depend for their existence on horizontal layering of some sort, and are always dispersive, *i.e.*, waves of different period travel with different phase and group velocities. Rayleigh waves are somewhat similar in particle motion to surface gravity waves in water, but the acting force is elastic rather than gravitational. They can exist at the free surface of a homogeneous semi-infinite solid, in which case they are nondispersive. But in the actual case of the layered earth, they too are dispersive, because the shorter wavelengths are confined largely to the upper layers of comparatively low velocity, while the longer wavelengths penetrate more deeply and are affected by the higher velocities of the deeper layers. For use in ocean studies, Ewing and Press (1950), employing relationships derived by Stoneley (1926), have computed group velocity of the first- and second-mode Rayleigh waves as a function of period and water depth for a two-layer system consisting of sea water (compressional wave velocity 1.52 km/sec) overlying a solid with a compressional wave velocity of about 8.0 km/sec and a Poisson's ratio of 0.25. They made similar computations for two cases of a three-layer system. In one case the intermediate layer had a compressional wave velocity of 5.5 km/sec, corresponding to typical velocities of the "granitic" rocks making up the top 10 km or so of the earth's crust under continents. In the other case, a velocity of 6.9 km/sec, typical of velocities observed in the crust under the oceans, was assumed. From these computations, they concluded that a "granitic" layer more than 5.5 km thick under the ocean along the path from an earthquake epicenter to the recording station could be detected if it were present. Examination of seismograph records from earthquakes having propagation paths under the Pacific and Atlantic Oceans showed, in general, no granitic layer under either ocean except possibly beneath the Easter Island rise in the southeast Pacific.

For any given period the velocity of the shorter-period Rayleigh waves depends critically on the depth of the overlying liquid layer. Because the sediments behave as if they were part of this layer, it is possible to determine the approximate thickness of sediments by comparing the computed depth of the liquid layer with that observed from soundings. Sediment thicknesses between about 500 and 1000 m in both the Pacific and Atlantic were obtained in this way by Oliver, Ewing, and Press (1953).

For Love waves traveling in a system of two rock layers, the longer-period waves approach the shear velocity in the lower medium, the duration of the train is determined largely by the difference between the two shear velocities, and the distribution of periods depends upon the thickness of the upper layer. Thus an examination of the train of Love waves on a seismograph record makes possible a rough determination of the elastic properties and geometry of the crustal layers along the line of propagation. Results obtained from studies of Love-wave records by Oliver, Ewing, and Press are similar to those obtained with Rayleigh waves.

Seismic refraction and reflection studies on shipboard using explosives as a sound source give more precise and detailed data for determining the crustal structure than seismograph records of earthquakes. In this method two vessels are used, a shooting craft and a receiving ship. A series of explosive charges is fired at depths of 100 to 300 ft beneath the sea surface, at predetermined distances from the receiving ship. The travel times between source and receiver are measured. Such travel-time data rarely yield a unique picture of the surface substructure, but in most situations it is possible to set up a model of subsurface velocities consistent with the observed travel-time curves. This model may resemble the true structure to a greater or lesser degree, depending on the local conditions and on the control achieved in shooting operations. The model ordinarily adopted assumes the existence of rock layers of constant sound velocity superimposed one on another, with each deeper layer having an appreciably higher velocity than the one above it (Raitt, 1952).

Figure 12.5 illustrates a subsurface section consisting of three layers with a velocity c_0, c_1, and c_2 respectively. In seismic work at sea, the upper layer is water. The receiving station is designated as A and the shot point as M. Sound rays are shown refracted through the third layer. The travel time T_{AM} from M to A is given by

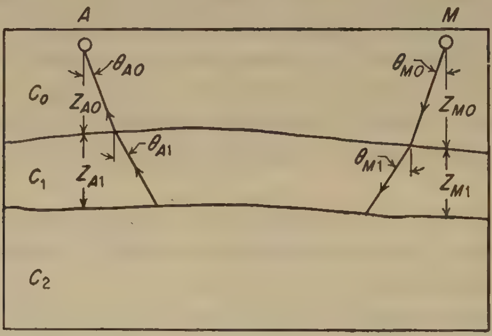


Fig. 12.5 Ray path of sound wave refracted through a rock layer beneath the sea floor. (*From Raitt*, 1952.)

$$T_{AM} = \frac{X_{AM}}{c_2} + \frac{Z_{A0}\cos\vartheta_{A0}}{c_0} + \frac{Z_{M0}\cos\vartheta_{M0}}{c_0} + \frac{Z_{A1}\cos\vartheta_{A1}}{c_1} + \frac{Z_{M1}\cos\vartheta_{M1}}{c_1}$$

where X_{AM} is the horizontal distance from shot to hydrophone and the Z's and ϑ's have the meaning shown in the figure. The term $(T_{AM} - X_{AM}/c_2)$ is called the *intercept time*. The four remaining terms are called *delay times* and are designated τ_{A0}, τ_{M0}, τ_{A1}, and τ_{M1}, respectively. In the typical deep Pacific Ocean τ_{A0} and τ_{M0}, called the *water delays*, are each of the order of 3 sec and are generally much larger than the delays pertaining to subsurface structure. Hence when the topography is irregular, the form of the travel-time plot is determined by bottom topography to a greater extent than by the underlying structure. These water delays are analogous to the "weathering" corrections of seismic surveying on land. The first step in the interpretation of the data is to subtract them from the observed travel times. After making this correction for water delay, the resultant travel-time data effectively represent the travel times that would have been observed if the shots and detectors had been placed on the sea bottom directly under the shot and detection positions. If the rock layers are flat or gently sloping, the velocity in the underlying rock layer is given approximately by $c_2 = 1/(dT'_{AM}/dX_{AM})$, where T'_{AM} is travel time corrected for water delay, and the thickness of the overlying rock layer underneath the receiving ship is given by

$$Z_{A1} = \frac{c_1\tau_{A1}}{\sqrt{1 - (c_1/c_2)^2}}$$

Maximum ranges obtained by this technique depend on the background noise produced by the motion of the hydrophones through the water. In the region of the northeast Pacific tradewinds, Raitt has obtained maximum ranges in kilometers Δ given by $\Delta = 7W^{1/2}$ where W is weight of explosive in pounds.

Evidence from earthquakes suggests that the crust beneath the oceans is thinner than beneath continents and that granitic rocks are absent. Seismic refraction work at sea has confirmed the absence of granite and has shown quantitatively how remarkably thin the crust really is. Raitt (in *Capricorn*, 1953) has found in the Pacific that typical values of this thickness (defined as the distance between sea bottom and the Mohorovičić discontinuity) are 5 to 10 km, compared with a thickness of 30 to 40 km beneath continents. Above the discontinuity, a zone with an average sound velocity of 6.8 km/sec exists. Above this layer, there is often a zone of variable thickness around 1 km, with a velocity between 4.5 and 5.5 km/sec. Just beneath the sea floor there is usually a veneer of sediments 100 to 400 m thick. Velocities between 5.5 and 6.5 km/sec corresponding to the "granitic" zone on land are not obtained under the sea floor.

Over the Easter Island rise seismic velocities greater than 8 km/sec were not observed by Raitt; the maximum velocities at depths greater than about 7 km were 7.2 and 7.9 km/sec. Over the Melanesian subcontinent, two of Raitt's stations gave maximum velocities of 7.5 and 7.9 km/sec at depths greater than about 7 km, while two others (one in the Fiji basin where the water depth is more than 2000 fathoms, the other between Alexa Bank and Fiji) gave typical "Moho" velocities. Above 7 km, velocities and thicknesses in both subcontinental areas are essentially similar to those in the deep Pacific basin. The sea floor over the Easter Island rise and the Melanesian subcontinent is about 1000 fathoms shallower than in the deep Pacific. Thus if these areas are in isostatic equilibrium, there must be significant differences in density distribution below 7 km between the subcontinental and the oceanic areas.

12.4 Heat Flow from beneath the Sea Floor

In measuring the heat flow through the sea floor two quantities are determined, the temperature gradient in the bottom sediments and the thermal conductivity of the sediments.

A first attempt to measure temperature gradients in the sea bottom was made on the Swedish *Albatross* Expedition in 1947–1948. E. C. Bullard and A. E. Maxwell designed a gradient recorder at the Scripps Institution in 1949. Further development was carried out by J. D. Isaacs, J. M. Snodgrass, and Maxwell, and the instrument was first used successfully on the Scripps Institution–Navy Electronics Laboratory *Mid-Pacific* Expedition in 1950 (Revelle and Maxwell, 1952). Improved models were later used by Maxwell in the Pacific and by Bullard in the Atlantic.

The instrument (Fig. 12.6) measures the difference in temperature between two points in the bottom sediments, one about 2 and the other 8 ft beneath the sea bottom. It consists of a hollow steel spear 10 ft long and 1.64 in. in outside diameter in which thermistors have been placed near each end. The spear is attached at its upper end to a water- and pressure-tight chamber, within which there is a battery-powered self-balancing null-type potentiometric recorder. From a 30-min continuous record of the temperature difference between the two thermistors, it is possible to deduce the undisturbed temperature gradient in the sediments. A core is obtained at the same station, and samples of the sediments are carefully preserved for laboratory determination of thermal conductivity. The product of the conductivity and the temperature gradient gives the heat flux through the sea floor.

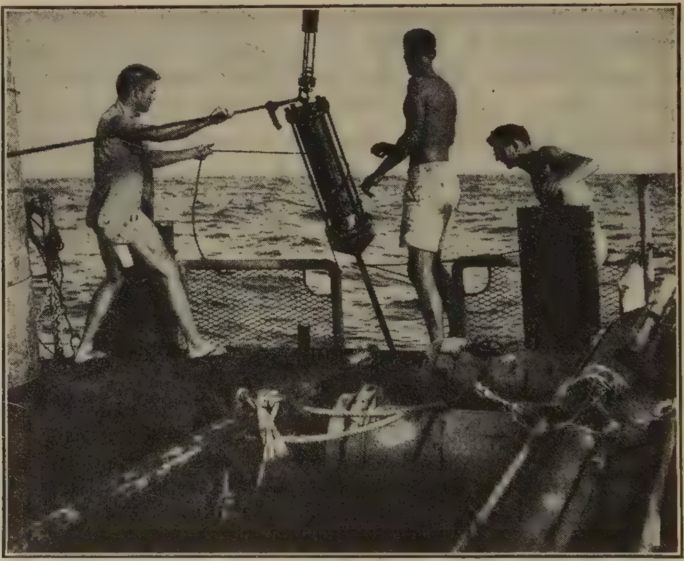


Fig. 12.6 Probe for measuring temperature gradients in deep-sea sediments being lowered from the research vessel *Spencer F. Baird.*

The results of these measurements over wide areas of the Pacific show that the amount of heat flowing through the sea floor averages close to 40 cal/(cm^2)(yr), about the same as that coming from the land. It can easily be shown that this quantity of heat cannot be accounted for by cooling of the earth and probably not by chemical processes within the interior. It must result from the decay of radioactive elements contained in the rocks of the crust and mantle.

Table 12.3 Radioactive Heat Generation in Typical Rocks*

Kind of rock	Concentration, g/g			Heat production, 10^{-6} cal/(g)(yr)			
	U × 10^6	Th × 10^6	K	U	Th	K	Total
Granite	4	13	0.04	2.9	2.6	1.1	6.6
Basalt	1	3	0.012	0.7	0.6	0.3	1.6
Dunite	0.014	?	0.0003	0.01	(0.01)	0.01	0.03
Stony meteorites	.....	..	0.002	....	....	0.05	

* From Birch, 1951.

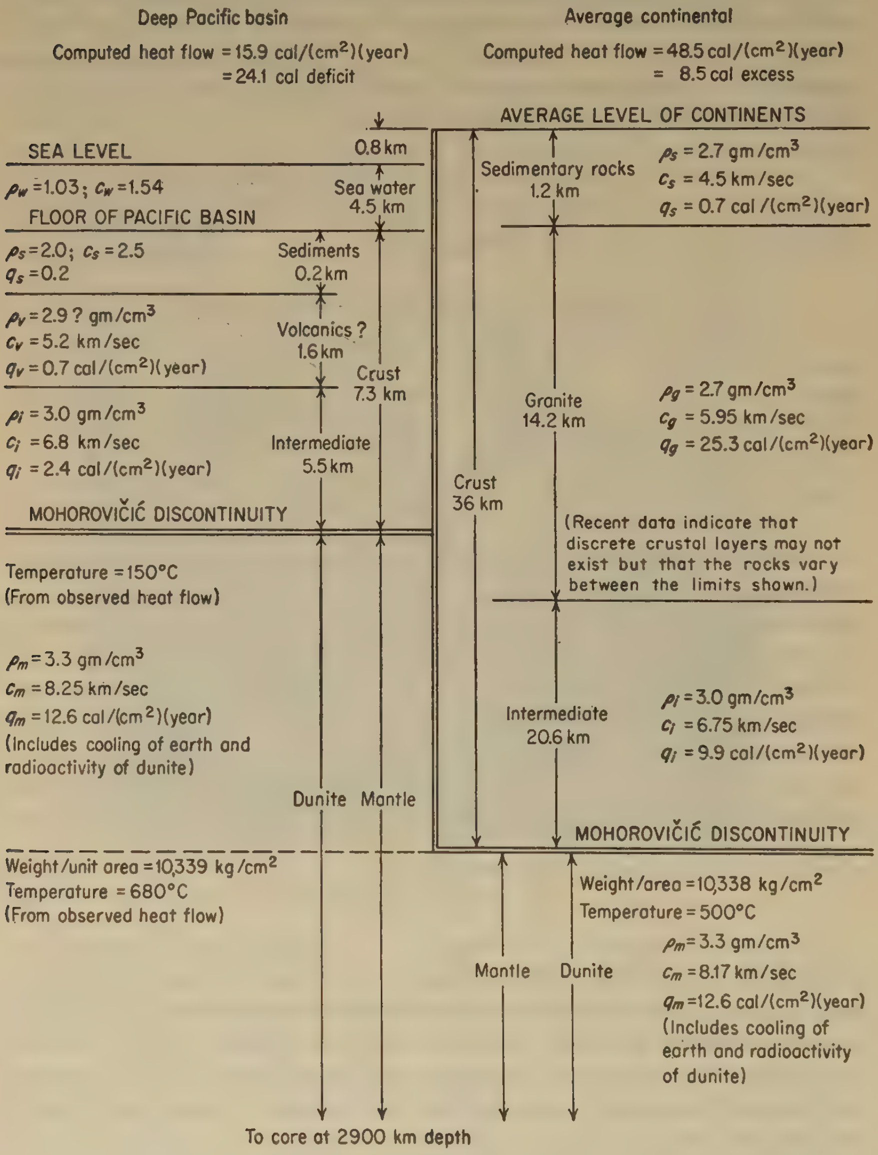
Under the continental platforms the presence of granitic rocks high in uranium and thorium furnishes an adequate source for the observed heat flow, but the seismic results for ocean areas show that granitic rocks are absent there, and even the layer of basaltic rocks is thin. If the source of heat is radioactive decay in the mantle, much heat must originate deep within the interior, but here we are faced with a paradox. If the radioactivity is distributed through too great a depth, the temperature near the base of the radioactive layer will rise above the melting point at that depth. The latter can be deduced from the Clausius-Clapeyron equation:

$$\frac{dT}{dZ} = \frac{gT(1 - \rho_1/\rho_2)}{L}$$

where T is the melting point in degrees absolute, L is the latent heat of fusion, and ρ_1 and ρ_2 are the densities of the liquid and the solid. At ordinary pressures $T = 1300°\text{C}$, $L = 4 \times 10^9$ ergs/g, and $1 - \rho_1/\rho_2 = 0.08$, which gives a melting point gradient of 3°C per km. At the pressures deep within the earth's interior, the melting-point gradient will be even less than this value.

On the other hand, if the radioactive layer is made too thin, the rocks beneath the ocean will have to be assumed to contain an amount of radioactive material that is difficult to reconcile with the observed sound velocities.

Table 12.4 Simplified Model of Pacific and Continental Structures (Computed for isostatic balance, 35.2 km below sea level)


Deep Pacific basin
Computed heat flow = 15.9 cal/(cm²)(year)
= 24.1 cal deficit
Average continental
Computed heat flow = 48.5 cal/(cm²)(year)
= 8.5 cal excess
AVERAGE LEVEL OF CONTINENTS
0.8 km
SEA LEVEL
ρw = 1.03; cw = 1.54
Sea water
4.5 km
FLOOR OF PACIFIC BASIN
ρs = 2.0; cs = 2.5
qs = 0.2
Sediments
0.2 km
ρv = 2.9 ? gm/cm³
cv = 5.2 km/sec
qv = 0.7 cal/(cm²)(year)
Volcanics ?
1.6 km
Crust
7.3 km
ρi = 3.0 gm/cm³
ci = 6.8 km/sec
qi = 2.4 cal/(cm²)(year)
Intermediate
5.5 km
MOHOROVIČIĆ DISCONTINUITY
Temperature = 150°C
(From observed heat flow)
ρm = 3.3 gm/cm³
cm = 8.25 km/sec
qm = 12.6 cal/(cm²)(year)
(Includes cooling of earth and radioactivity of dunite)
Dunite
Mantle
Weight/unit area = 10,339 kg/cm²
Temperature = 680°C
(From observed heat flow)
To core at 2900 km depth
Sedimentary rocks
1.2 km
ρs = 2.7 gm/cm³
cs = 4.5 km/sec
qs = 0.7 cal/(cm²)(year)
Granite
14.2 km
ρg = 2.7 gm/cm³
cg = 5.95 km/sec
qg = 25.3 cal/(cm²)(year)
Crust
36 km
(Recent data indicate that discrete crustal layers may not exist but that the rocks vary between the limits shown.)
Intermediate
20.6 km
ρi = 3.0 gm/cm³
ci = 6.75 km/sec
qi = 9.9 cal/(cm²)(year)
MOHOROVIČIĆ DISCONTINUITY
Weight/area = 10,338 kg/cm²
Temperature = 500°C
ρm = 3.3 gm/cm³
cm = 8.17 km/sec
qm = 12.6 cal/(cm²)(year)
(Includes cooling of earth and radioactivity of dunite)
Mantle
Dunite

It can be shown that the melting point would be exceeded if the thickness of the radioactive material were greater than about 150 km. The heat generation needed to give a heat flow of 1.2×10^{-6} cal/(cm^2)(sec) would be 5.3×10^{-14} cal/(cm^3)(sec) for a 200-km layer and 9.2×10^{-14} for a 100-km layer after allowance has been made for original heat and for that from 7 km of basalt. These values are so much greater than the observed average of 0.4×10^{-14} cal/(cm^3)(sec) for ultrabasic rocks as to raise a real difficulty.

The preceding computations rest on the assumption that the heat flow is by molecular conduction. If convection plays a role, *i.e.*, if the rocks in the earth's mantle are slowly overturning, the observed heat flow can easily be accounted for. But other considerations, notably inhomogeneities deduced from seismic velocities in the upper 500 km of the mantle, argue powerfully against the possibility of convection.

Table 12.4 summarizes some of the possible inferences from data given in previous pages concerning the constitution of the outer parts of the earth beneath the continents and the oceans. It will be seen that the assumed densities and thicknesses of "layers" allow for isostatic equilibrium between the continental masses and the crust and mantle beneath the sea but that the computed heat flow through the sea floor, based on the assumption that the mantle under the ocean is like that under the continents, is much too small.

12.5 Deep-sea Sediments

The sediments of the deep sea may have constituted by far the larger part of all sediments formed throughout geologic time. Thus the geochemical transformations of the earth's crust during the past 3 billion years cannot be adequately understood until we have a more complete knowledge of the deep-sea deposits.

These sediments are unique in one most important respect. They are rarely if ever uplifted to form sedimentary rocks on land. No example is known of sedimentary rocks above sea level which are unquestionably of deep-sea origin. We must conclude therefore that the processes of weathering, erosion, and sedimentation have brought about a loss of materials from the continents to the deep-sea floor. The total amount of material thus lost from the continents could be computed if we knew the average rate of sedimentation on the sea floor throughout geologic time, or on the other hand, if we knew the total amount of material which had been weathered and the portion retained on the continents as sedimentary rocks or reincorporated in igneous rocks.

The relative amounts of deep-sea sediments and of continental sediments may be estimated by comparing the average chemical composition of continental sedimentary rocks with that of the igneous rocks from which they are derived. For example, the sedimentary rocks contain nearly three times as much calcium as the source material. Unless the average composition of igneous rocks has changed during geologic time, this must mean that for every gram of continental sedimentary rock nearly 3 g of igneous rock has been used up and that the mass of sediments transported to the deep sea is at least twice as great as the mass of continental sediments. From this and similar geochemical computations, Kuenen (1950) concluded that the total mass of deep-sea sediments deposited throughout the geologic past is about six times the total mass of sediments remaining on the continents and that the thickness of the deep-sea deposits should be of the order of 3 km.

At the present time, the preponderant type of deposition on the deep-sea floor is of sediments high in calcium, namely, globigerina ooze and other calcareous oozes. If the deposition throughout the geologic past had been like that at the present time, it would be impossible to arrive at a geochemical balance, because both the deep-sea and continental sediments would be higher in calcium than the igneous rocks from which they are derived. Thus we arrive at another most important conclusion, namely, that the character of the deposition on the deep-sea floor has changed radically with time; throughout most of geologic history, deep-sea sediments must have been lower in calcium than the average igneous rocks, whereas the present deposits have an excess of calcium.

Except for calcium and magnesium, all the major elements are more abundant in igneous rocks than in continental sedimentary rocks; hence these elements must have become concentrated either in solution in the sea itself, as in the case of sodium, or in the deep-sea sediments. This concentration in the deep sea is particularly striking for manganese, phosphorus, titanium, and iron. The sedimentary rocks of the continents contain only 10 per cent as much manganese and 30 per cent as much iron, phosphorus, and titanium as igneous rocks. Analyses of deep-sea sediments suggest that many of the minor elements, *e.g.*, nickel and cobalt, have likewise been concentrated on the sea floor.

In areas of little horizontal transport near the bottom, a core 10 m long penetrates a continuous sequence of sediments laid down over hundreds of thousands and perhaps millions of years. When such a core is examined (Arrhenius, 1952), marked stratification is observed—the different strata must reflect variations in conditions of deposition and hence must constitute a record of past oceanic climate. For example, in the "eupelagic" area of the eastern tropical Pacific, the topmost layer of the cores is usually considerably lower in calcium carbonate and in number of diatoms but contains more shells of certain warm-water species of Foraminifera than the material 10 to 25 cm below the surface. As we go downward in the core, we pass through a series of alternating layers. The fluctuations in calcium carbonate content become smaller in amplitude near the bottom of the core.

Similar alterations between layers of high and low calcium carbonate occur in the tropical Atlantic (Schott, 1935) but with the remarkable difference that in many cores the surface layer is higher in calcium carbonate than the layer 25 cm below the surface.

Both of these sequences are believed to reflect changes in oceanic circulation and in the character of the surface waters during the glacial and interglacial stages of the Pleistocene. The top layers in both cases may have been deposited since the last retreat of the glacial ice.

Arrhenius has correlated the layers of high calcium carbonate, high diatoms, and low warm-water foraminifera in the tropical Pacific with the Pleistocene glacial stages. He supposes that during epochs of maximum glaciation the trade winds were narrowed and intensified. The resulting stronger divergence in the wind system near the equator would bring about a corresponding divergence of the surface waters accompanied by marked upward motion of nutrient-rich deeper water. Organic productivity would thus be greatly increased, the rate of precipitation of calcium carbonate and silica in the shells of planktonic plants and animals would be accelerated, and the quantity of shell material settling through the water would be increased. At the same time the circulation of the deep cold waters of the ocean would speed up; correspondingly the rate at which calcium carbonate would be dissolved in these deep waters would increase. Arrhenius believes that in the Pacific the increased productivity would overbalance the increased rate of solution. Hence the glacial stages were periods of high calcium carbonate deposition. In the Atlantic the intensification of the trade winds and of the vertical water circulation in the equatorial zones was much less pronounced, while the acceleration of the deep-water circulation was greater. Hence glacial stages were times of relatively low calcium carbonate deposition.

This hypothesis differs radically from the explanation proposed by Schott (1935) and now widely held. Schott proposed that the surface waters of the tropics were cooled by as much as 10°C during the glacial stages, with the result that organic precipitation of calcium carbonate was greatly reduced. At the same time, because of the relative elevation of the continents, their contribution to the sea floor was perhaps increased. Hence the deposits laid down during glacial periods should be low in calcium carbonate, while those of interglacials or postglacials such as the present should have high calcium carbonate content.

Actually the hypotheses of Schott and Arrhenius are not necessarily contradictory. In some regions cooling of the surface waters may have had the predominant effect on tropical pelagic sediments during the glacial period; in others the increased organic productivity brought about by the intensified atmospheric and oceanic circulation may have been most important; elsewhere, the increased circulation of bottom water may have resulted in solution of calcium carbonate before it could be buried, thereby determining the character of the sediments.

Many attempts have been made to estimate the rate of deposition of deep-sea sediments. The finding of fossil shark's teeth in dredge hauls led earlier workers to suppose that these deposits were laid down at an almost infinitesimally slow rate, less than 0.1 mm per 1000 yr. More recent workers have based their estimates on the occurrences of glacial and postglacial strata in cores. Assuming that 20,000 years have elapsed since the end of the ice age and finding an average thickness for the topmost postglacial layer of about 20 cm, they have concluded that the present rate of deposition is about 1 cm per 1000 yr. Similar results have been achieved by investigators who have used the decrease in radioactivity (which must come largely from the uranium-ionium-radium series) with depth in the cores as an index of the time since deposition of different layers. Both of these methods are subject to considerable uncertainty. The first essentially begs the questions of whether the different layers in the sediments can be correlated with Pleistocene glacial and interglacial stages and whether the oceanic circulation of the tropics synchronized with the retreats and advances of the ice in North America and northern Europe. The second method is questionable because absorption and diffusion of uranium and ionium in different constituents of the sediments may seriously distort the radioactive equilibrium. Moreover the rates of decay of uranium and ionium are too slow to give the precision needed for accurate dating of late Pleistocene and post-Pleistocene events. The successful use of radioactive carbon 14 as a means of dating carbon-containing materials from a few hundred to several tens of thousands of years old suggests its application to the problem of dating the upper layers of the sediments. Because of the amount of carbon required for the analysis, this method can be applied only to carbonate-rich calcareous ooze. Carbon 14 age determinations in cores of this material have been made by Arrhenius, Kjellberg, and Libby (1951) who conclude that the rate of deposition is about 10 cm per 1000 yr. This rate is undoubtedly at least ten times greater than that of the deep-sea deposits as a whole.

The thickness of the sediments has been one of the principal objects of the seismic refraction and reflection studies. We have already seen that geochemical considerations require a thickness of deep-sea sediments of the order of 1 to 3 km. Raitt's seismic refraction results indicate that the actual thickness of materials having a velocity less than about 4.5 km/sec is nearly everywhere less than 500 m. Velocities of 4.5 km/sec or more are unlikely to represent consolidated sediment, unless it be a crystalline limestone, and it has already been pointed out that during earlier geological time the percentage of lime in the deep-sea deposits must have been quite low. We are faced with another dilemma—either the geochemical calculations are wrong, or the lower layers of the sediments have somehow disappeared. At the present rate of deposition of about 1 cm per 1000 yr, the measured thickness of sediments would represent a total time of deposition of less than 50 million years. Allowing for compaction and for lower rates of deposition prior to the Pleistocene, the maximum thickness of sediments corresponds at most to a few hundred million years. We are thus almost forced to the conclusion that, if deposition of sediments was taking place in the deep Pacific prior to the late Mesozoic, these earlier deposits have disappeared or are not now detectable by seismic methods.

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SIZE DISTRIBUTION, EROSIVE ACTIVITIES, AND GROSS METABOLIC EFFICIENCY OF THE MARINE INTERTIDAL SNAILS, LITTORINA PLANAXIS AND L. SCUTULATA [1, 2]

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The two common representatives in Southern California of the nearly world-wide genus, *Littorina*, are *L. planaxis* and *L. scutulata*. The former generally occurs at higher levels in the intertidal, but the zones of distribution of the two species overlap. *L. planaxis* may often be found 5 to 10 feet above spring high tide level, but *L. scutulata* prefers a zone two or three feet on either side of the high tide mark. Published information concerning these two species of snail is scanty in spite of their great abundance and their availability. Their importance to the high intertidal community, however, warrants an extensive study of their ecology, and the present paper describes some of the basic biology of these interesting animals.

Size Distribution

Inspection of colonies of *Littorina* at different places along the La Jolla shore has revealed that the majority of snails at any given locality fall within certain rather well defined size limits. Lysaght (1941) noted a similar condition in *L. neritoides* on the Plymouth Breakwater. In order to gain a more exact picture of size distributions in the present study, three typical *Littorina* environments were chosen, and height measurements were made of all the periwinkles found within a selected area, representative of the environment.

Environmental description

The three environments are shown in Figure 1. The first (Fig. 1a) is a group of pools at Whale View Point in La Jolla. The area is subjected to vigorous wave action as even moderate tides. The second environment (Fig. 1b) is the seaward edge of the top of a broad shelf of rock that extends out from a cliff about 1/4 mile north of the Scripps Institution of Oceanography. The top of Shelf Rock is 1 to 1½ meters above spring tides, but the area under discussion is well splashed at high tide and a large wave may occasionally wash over it. The

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[2] Contribution from the Scripps Institution of Oceanography, New Series No. 685.

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third environment (Fig. 1c) is a protected portion of Shelf Rock some three meters removed from the second environment and splashed only occasionally by large waves.

All three localities are sedimentary sandstone, but the grain size is much finer at Shelf Rock. By exerting pressure the point of a knife may be forced into

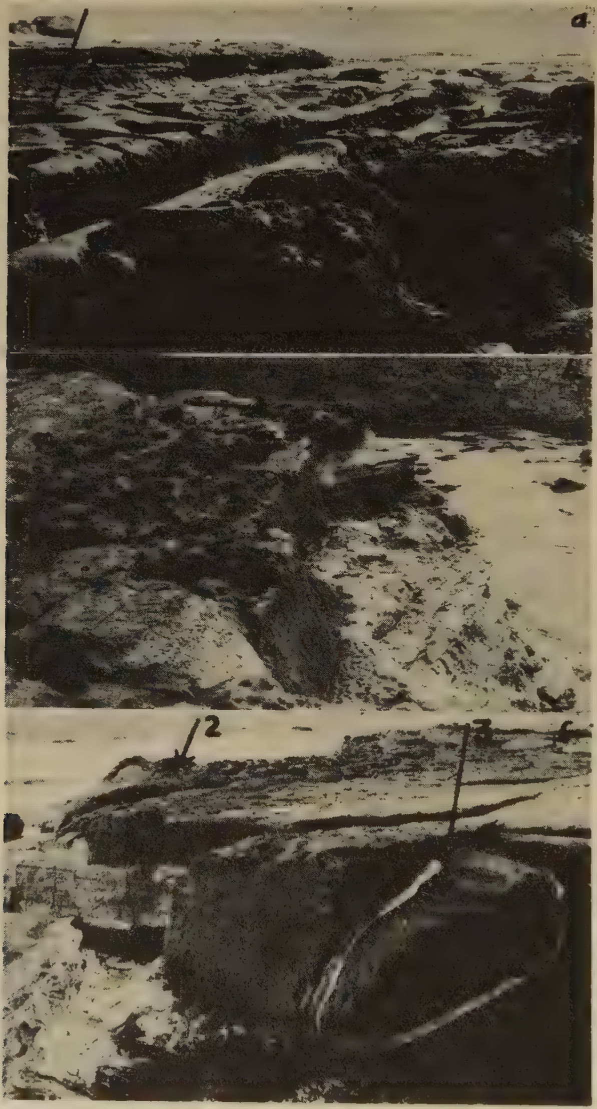

FIGURE 1. Photographs of the three environments studied. *a.* Whale View Point; arrow points to typical tidepool from which snails were gathered. *b.* Pools of Shelf Rock; arrow points to region studied. *c.* Dry area of Shelf Rock; Region studied enclosed by white line and marked with arrow labeled 3: arrow labeled 2 points to second environment, about 3 meters away.

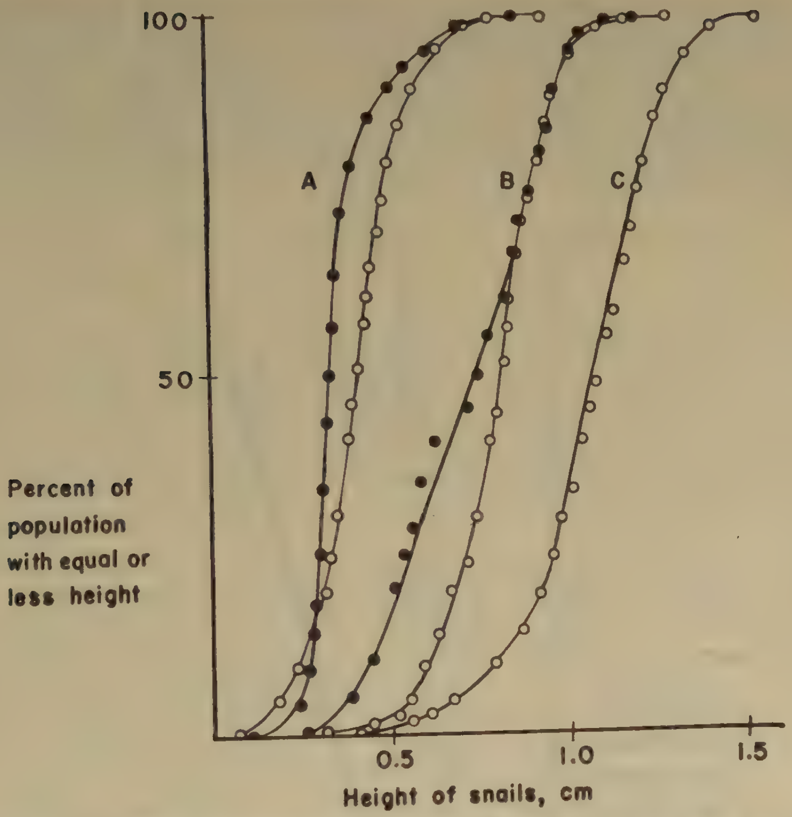

FIGURE 2. Cumulative curves for the *Littorina planaxis* populations of three environments. A. Whale View Point; B. Shelf Rock pools; C. Dry area, Shelf Rock. Measurements made in August, 1951, shown as circles; measurements made in July, 1953 shown as dots.

the sandstones to a depth of about half an inch. The top layers of sand particles may easily be removed by scraping. The topography is characteristically very irregular, great numbers of pools, depressions, basins, and small holes being present.

Results of measurements

The size distribution of *L. planaxis* and *L. scutulata* in each of these environments is shown by means of cumulative curves in Figures 2 and 3. The greatest dimension, "height," was measured, being the distance from the tip of the spire to the lower lip of the aperture. It can be seen that the populations at Whale View Point are rather small, averaging about 0.4 cm. The snails in the pools of Shelf Rock are generally intermediate in size, approximately 0.8 cm., while those on the sheltered dry area of Shelf Rock, although more heterogeneous than the other groups, are generally the largest, averaging almost 1.1 cm. in height. In the latter environment there were insufficient numbers of *L. scutulata* to enable the construction of a reliable curve.

In attempting to explain the variation in size distribution with locality, two possibilities suggest themselves. A favorable set of spawn in different areas at different times, for example, would produce curves of the type that have been obtained. Equally plausible is the contingency that some factor or factors operate in the environment to produce selection for a particular size of periwinkle. If the first hypothesis is correct, curves obtained from measurements made at a later date should be shifted towards the right along the abscissa; that is, effects of growth should be evident. If the latter hypothesis is the proper explanation for the phenomenon, the position on the abscissa of a curve should remain constant with time. Figures 2 and 3 show cumulative curves for populations in the first and second environments, constructed from measurements made about two years after the data discussed above were obtained. Measurements were not attempted for the third environment as appreciable numbers of large periwinkles had been permanently removed from this locality for other experiments. The expected

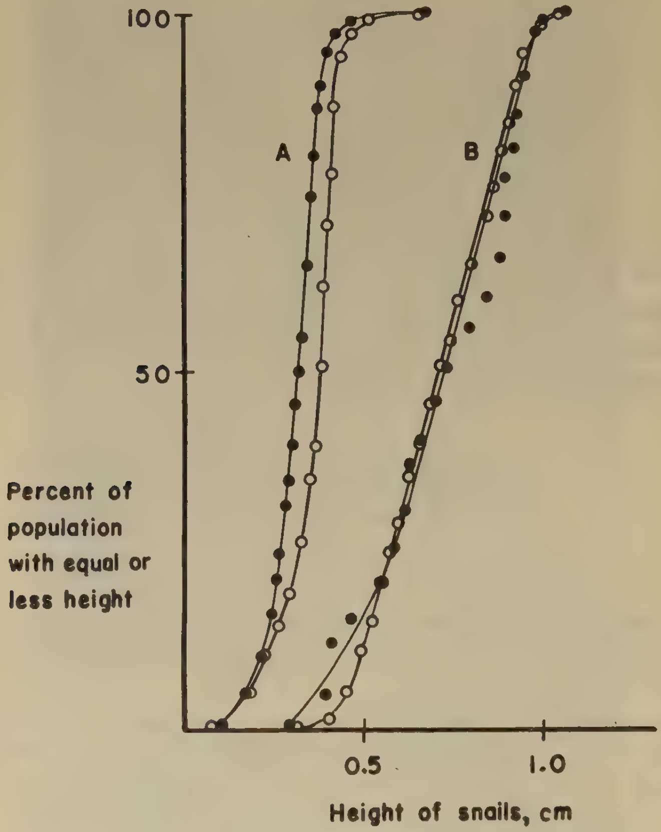

FIGURE 3. Cumulative curves for the *Littorina scutulata* populations of two environments. A. Whale View Point; B. Shelf Rock pools. Measurements made in August, 1951, shown as circles; measurements made in July, 1953, shown as dots.

height increase of *L. planaxis* during this time can be calculated from data given below, and would be of the order of 0.5 cm., but the two sets of curves occupy approximately the same position. Environmental factors, therefore, appear to determine the size distribution of snail populations at any particular locale.

It should be mentioned that the three environments were under constant observation over the period that intervened between the measurements of Figures 2 and 3. The populations were never noticeably different in their size distribution during this time.

Factors affecting size

Wave action and salinity may be among environmental mechanisms capable of causing selection for a given snail size. In many places these two factors are inversely correlated. The higher levels of the spray zone are not wetted by the ocean so frequently as are the lower levels, and have therefore more opportunity for undergoing evaporation and achieving correspondingly greater salinities. The water of the pools and the surface moisture films of the lower levels, on the other hand, are renewed often by waves, and salinities at these localities are therefore not elevated.

As already noted, the three environments studied are subjected to different degrees of wave action. The snail populations composed of larger individuals appear to occupy the drier areas of the spray zone. In order to determine whether water currents might be more effective in removing large than small snails the following experiments were performed.

Four small (approx. 0.6 cm.), four intermediate (0.9–1.2 cm.), and four large (1.4–1.6 cm.) specimens of *L. planaxis* were placed on a small flat rock in a tidepool. When all the snails had emerged from their shells and were observed creeping, the rock was moved rapidly through the pool, creating a water current across the shells. After several vigorous swings through the water, only three small snails were left. A repetition of the experiment using six small, four intermediate, and four large snails ended with only four small snails remaining attached to the rock. When twelve medium-size *L. scutulata* (approx. 0.9 cm.) were placed on the stone with three small and two large *L. planaxis* for comparison purposes, the large specimens of the latter species were washed off with relative ease. After much effort three of the *L. scutulata* were eventually swept away, leaving nine of this species and the three small *L. planaxis* when the experiment was discontinued.

When a stream of sea water from a hose was allowed to play against the shells of *L. planaxis* creeping on a flat rock, large individuals were washed off more readily than small ones, and a snail of a given size was removed with greater ease when the stream was directed against the posterior part of the shell.

In order to gain an idea of the current velocities necessary to dislodge a snail, specimens of *L. planaxis* were placed in a Plexiglass tube of 3.5 cm., inside diameter, and after the animals had emerged from their shells and were crawling on the surface of the Plexiglass, the tube was gently filled with sea water. A current of known velocity was then allowed to flow through the tube and notations were made of the ability of the snails to remain attached for 10 seconds. The results are given in Table I. A total of 10 large and 8 small snails was used in the experiment, and 6 trials were conducted.

Several hypotheses offer plausible explanations for the ability of small *L. planaxis* to withstand currents that remove large individuals. Physical factors might include greater water friction acting as drag on larger shells, or frictional forces slowing the current in the vicinity of the rock-water interface[3] thus favoring smaller snails. Biological factors might include loss of vigor and of tenacity with increasing age, or a disproportionate growth of the various parts such that the sole of the foot does not increase as rapidly as the surface area of the shell. Figure 4 shows that the last hypothesis is not supportable, hence one or more of the other factors may contribute to the distribution phenomenon.

TABLE I

Effect of current velocity on two size groups of Littorina planaxis

Size group	Velocity of current flowing over snails meters/second	Fraction of snails removed by current per cent
Large snails (1.3 to 1.6 cm.)	3.4	90
	2.3	90
	2.0	80
Small snails (approx. 0.7 cm.)	3.4	50
	2.0	50

The absence of large snails from areas exposed to vigorous wave action may thus be explained, but account has not yet been taken of the absence of small snails in the high, dry areas of the spray zone. The solution to this problem may lie in physiological age changes rendering the animal more capable of coping with exposure to air or to more variable salinity conditions. Salinity has been shown to influence shell size and shape in *Littorina* (Thorson, 1946; Agersborg, 1927) and further study along these lines will be necessary before a complete explanation of the observed size distribution can be proposed.

EROSIVE ACTIVITIES

Many intertidal animals bring about erosion of rock. *Littorina* species often occur in small basins above high water mark (Fischer-Piette, 1932; Clench, 1938; Lysaght, 1941) and have been credited by some investigators (Brunelli, 1928; Welch, 1929) with the production of depressions in rock. The snails feed by applying a file-like ribbon, the radula, to the substratum and transfer bits of it to the mouth by a scraping action. On the cliffs around La Jolla the animals scrape algae and fine detritus from the rocks and at the same time remove particles of the rock itself. Because of their great abundance, erosion resulting from their feeding is believed to be appreciable, and a quantitative estimation of the magnitude of the erosion will be useful in determining its importance with respect to other erosive processes.

Since the animals may not behave as they do in nature when kept in the laboratory over long periods of time, it seemed wisest to obtain as much data as possible from snails in their normal environment. The simplest means for accomplishing this appeared to be to determine the number of times daily the gut contents are completely renewed, and also the proportion of the gut contents that is inorganic matter. The product of the two quantities would yield the daily rate of erosion.

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[3] An idea for which I am indebted to Professor Roger R. Revelle.

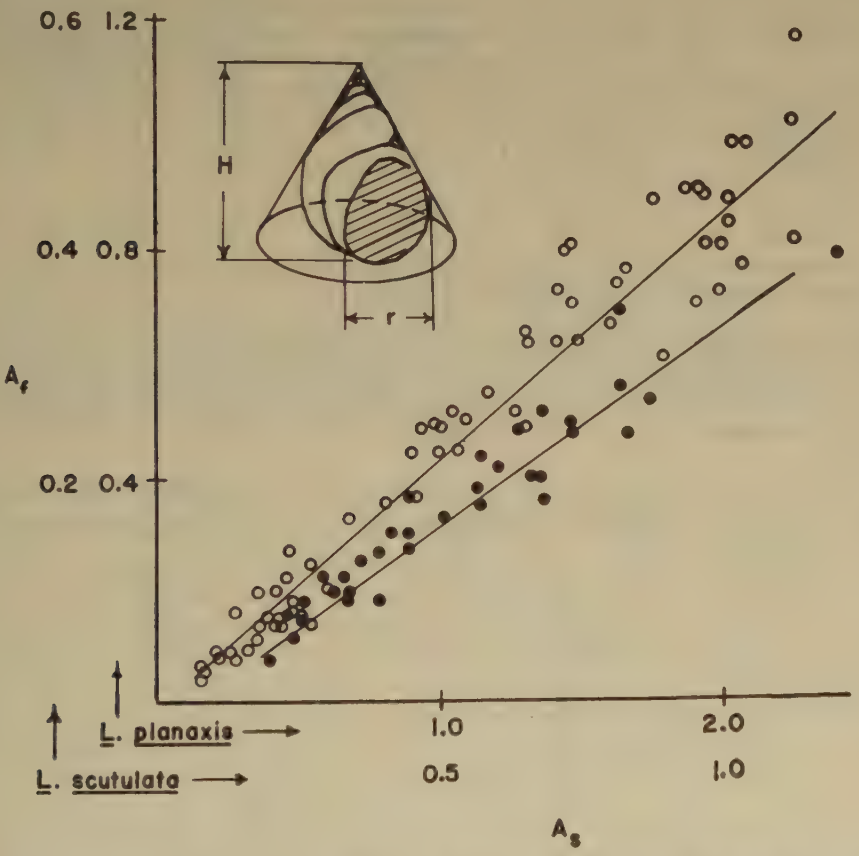

FIGURE 4. Relationship of shell surface to surface of the sole of the foot for *Littorina planaxis* and *L. scutulata*, indicating that the increase in area of each with age is proportionately the same. The sole area (A_f) was measured while the animals were crawling up the sides of a glass vessel. Shell surface (A_s) was arbitrarily taken as $1/\pi$ of $\pi \sqrt{r^2 + H^2}$, the formula for the curved surface of a right cone.

Time required to renew material in the gut

The number of times daily the gut contents are renewed will depend on the rate at which material is passed along the gut, which in turn may vary with the amount of time the snail is able to feed. Dissection of specimens of *L. planaxis* taken both from pools (46 specimens) and from areas that become dry at low tides (30 specimens) revealed that throughout the day the intestines of the former group were always full of unconsolidated material, whereas the intestines of the latter

TABLE II

Summary of an experiment to determine the time required for Littorina to cycle food completely through the gut; May 18, 1953; water temperature range 17° to 30° C.; 20 snails per size group

Species	Height cm.	Time elapsed until		
		First blue fecal pellet observed, hr.	Half of group defecated blue feces, hr.	Entire group defecated blue feces, hr.
L. planaxis	0.4–0.5	1⅔	2	3
L. planaxis	0.7–0.95	2	3¾	5
L. planaxis	1.3–1.6	2½	4⅔	–*
L. scutulata	0.3–0.45	1⅔	2	3
L. scutulata	0.8–0.95	2⅓	4	5

* Thirteen had defecated blue feces after 7½ hours.

group were generally at least partially full but sometimes almost empty. It was concluded that animals in the pools graze sufficiently to keep the gut full at all times. Snails feeding on areas that become dry at low tide appear to graze only when the surface is moist, and the amount of material in the gut consequently is variable.

In order to determine the rate at which material is passed through the gut, groups of snails were allowed to graze on a section of Shelf Rock stained with the

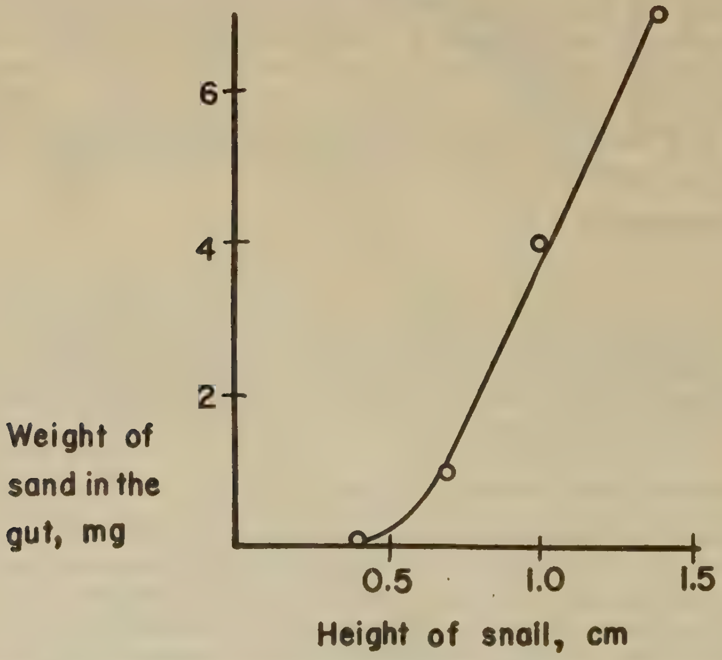

FIGURE 5. Relationship of sand contained in the gut to height of *Littorina planaxis*.

harmless dye methylene blue. After a period of an hour and a half had elapsed, the animals were removed to an unstained area and carefully observed for the first appearance of blue fecal pellets. While they were on the stained and unstained rock, the periwinkles were washed with fresh sea water every 10 minutes, and their behavior during the experiment seemed normal. Five such experiments were conducted on two spring and on three summer days. For snails of height 0.8 cm., cycling times of 2½ to 6 hours were obtained. The results were always similar and are described in Table II for one of the experiments.

A typical 0.8-cm. snail in a Shelf Rock pool, therefore, feeds sufficiently to keep the gut full at all times and probably renews the material completely four to eight times daily.

Inorganic matter in the gut

Sand in the gut was determined by extracting snails from their shells, incinerating the bodies in a tared crucible, cooling, adding a little concentrated hydrochloric acid to dissolve body ash, carefully decanting, rinsing, re-incinerating and weighing. Four size groups of 50 *L. planaxis* each were thus analyzed and the results are presented in the curve of Figure 5. An 0.8-cm. snail therefore contains on the average about 1.6 mg. of sand in the gut.

Calculated rate of erosion

Taking the Shelf Rock region, and considering the simplest case of a snail feeding in a pool, an estimation of erosion may now be made. It has been shown (Fig. 2) that the population in this environment averages 0.8 cm. in height. The average amount of inorganic material contained in the gut of an 0.8-cm. snail was found to be 1.6 mg., and, if we take the most conservative cycling period of 4 times daily, we obtain the value of $1.6 \times 4 = 6.4$ mg. of inorganic material passing through the gut of the snail per day. This presumably is equivalent to the amount of rock eroded daily. The density of Shelf Rock is approximately 2.5 g./cc. and calculations show that 100 snails, 0.8 cm. in height, would be capable of excavating a basin of 86 cc. yearly, almost a liter in a decade.

The concentration of *L. planaxis* in the environment under discussion is of the order of one snail per 30 $cm.^2$ Erosion by this species alone, therefore, may be calculated to deepen the pools one cm. every 40 years. If *L. scutulata* is considered, the snail concentration increases to one snail per 12 $cm.,^2$ and assuming that 0.8-cm. individuals of both species have similar feeding rates and weight of gut contents, erosion by both *Littorina* species combined will deepen the pools one cm. every 16 years. The snail concentration has remained fairly constant over the two-year period that is covered by these observations.

Comparison with erosion from other sources

Other erosive processes acting on the sandstone rocks of this area have been studied by Emery (1941, 1946). For exposed surfaces a general erosion rate of one cm. every 20 years was estimated, while for pools at Whale View Point nocturnal pH changes at low tides were calculated to cause a deepening of the pools by one cm. every 33 years. The different processes causing rock erosion are probably additive in some cases and in other instances facilitate each other and are not additive.

GROSS EFFICIENCY

The average, gross metabolic efficiency, or the ratio of ingested food to organic matter incorporated as living tissue, may now be estimated for *L. planaxis* with the aid of additional data that have been obtained.

Growth

Growth rates were determined by measuring the increases in height of marked specimens of *L. planaxis* on Shelf Rock at various intervals for a period of a year and a quarter. The methods of converting an increase in spiral length to a height increase, used by Moore (1937) and Lenderking (1951) with other littorines, seemed to be complicated in the present case, since the apex angle of *L. planaxis* varies considerably, and it therefore appeared simplest to measure height increments over a long period of time. Figure 6 illustrates the results of the experiment, showing the growths of positively identified individuals from the snails that were recovered, out of a total of 300 originally marked. It may be noted that an 0.8-cm. snail has an average height increment of about 0.02 cm. per month.

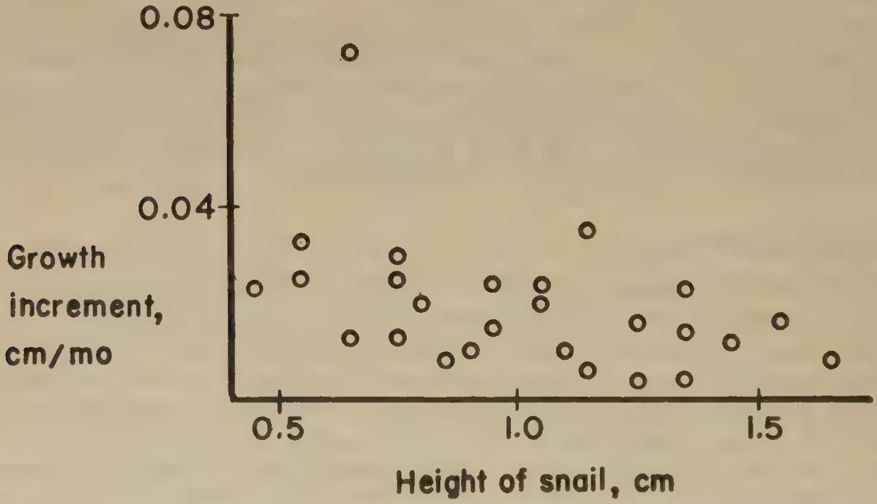

FIGURE 6. Twenty-six monthly growth increments observed in specimens of *Littorina planaxis* at Shelf Rock.

To convert this value to an increase in tissue weight the relationship between snail height and dry tissue weight was obtained and is shown in Figure 7. Specimens of *L. planaxis* were dried in a vacuum oven for 24 hours at 80° C. and 460 mm. pressure. After cooling in a desiccator, the shell and dry tissue were weighed and the shell weight was obtained after removing the dry tissue by a half hour's immersion in boiling 20% KOH. Dry tissue weight was then readily calculated

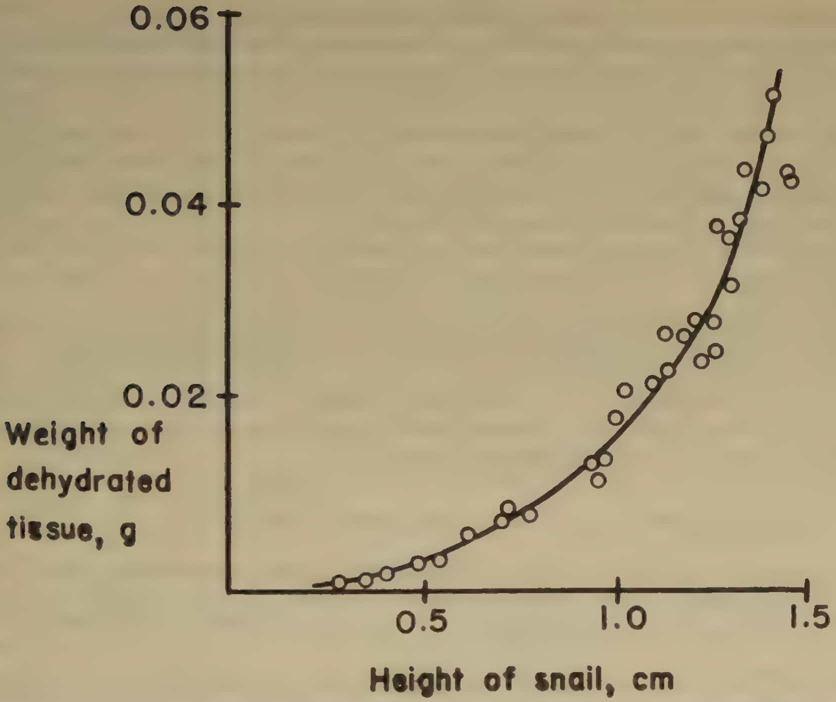

FIGURE 7. Relationship between dry tissue weight of *Littorina planaxis* and height.

by subtraction. Computations using Figure 7 indicate that an 0.8-cm. snail growing 0.02 cm. per month would have an increase in dry weight of 0.6 mg. for a like period.

Ingestion of organic matter

Determination of the amount of food ingested monthly could be readily accomplished if the organic matter per cent of the material swallowed by the snail were known. In scraping the surface of rocks, however, the snail has an excellent

TABLE III

Organic content of various materials

Material analyzed	Organic matter per cent	Average
Snail feces	2.4	
	2.0	
	3.0	
	3.2	2.7
Light manual knife scrapings of rock surface	2.4	
	2.6	2.5
Loose sand from tidepool bottom	0.8	
	1.0	0.9

mechanism for removing only a thin, organic-rich layer of material. Even the lightest of scrapings made by a knife might remove much underlying rock along with the surface "skin" of organic matter. To estimate the organic matter per cent of the material swallowed by the snail, therefore, it seemed best to assume that only a small fraction of the organic molecules will be assimilated through the gut wall, and that the feces would therefore have approximately (and conservatively) the same organic content as the ingested material. Corrections for this assumption can then be made and the efficiency recalculated.

Fresh snail feces may easily be obtained in abundance, and the results of organic analyses on these and other materials by Walkley and Black's rapid titration method (chromic acid digestion) are given in Table III.

It was found in calculating erosion that an 0.8-cm. snail voids 6.4 mg. of inorganic material daily and this amounts to 192 mg. per 30-day month. If the feces are 2.7% organic matter the amount of organic material voided per month is 5.3 mg. Making use of the assumption explained above, this is approximately equal to the monthly ingested organic matter.

Calculation of gross efficiency

For an 0.8-cm. snail in the pools of Shelf Rock the gross efficiency may now be estimated as $\frac{\text{Organic matter added as tissue}}{\text{Organic matter ingested}} \times 100$ which equals $\frac{0.6}{5.3} \times 100 = 11\%$.

In order to refine the calculation let us consider how much of the ingested organic matter might reasonably be assimilated across the gut wall from the food, of which some is built into new tissue. There must also have been assimilated a sufficient quantity of material to account for organic matter lost in respiration, and since the animals are poikilothermic and slow in movement, it would seem that this loss should be less than 4 times the amount added as new tissue. Taking the latter, then, as 20% of the total assimilated, and all other losses combined as 80%, and knowing that the animal adds 0.6 mg. per month as new tissue, we have 3 mg. per month as an estimate of the amount of organic matter assimilated across the gut wall. Recalculating the efficiency gives a value of $\frac{0.6}{5.3 + 3.0} \times 100 = 7\%$.

It will be recalled that in calculating erosion the time for cycling food through the gut was taken conservatively as 6 hours. The average value might be less, which would increase the erosion rate and depress the efficiency.

SUMMARY

1. Size distribution curves for populations of the marine intertidal snails *Littorina planaxis* and *L. scutulata* in three environments are presented.

2. It is concluded that environmental factors cause the observed size distributions, and the amount of wave action at a given locale appears to be one of the influencing factors. *L. planaxis* was observed to cling to a smooth surface in current velocities of two to three meters per second for 10 seconds.

3. The time for littorines to cycle food completely through the gut varied with size. Snails 0.8 cm. in height required from 2½ to 6 hours.

4. Erosion resulting from the snails' feeding activities was estimated for certain tidepools and found to deepen tidepools one cm. every 16 years. This is of the same order of magnitude as other erosive processes which have been studied in the same region.

5. Growth of *L. planaxis* was found to average 0.02 cm. per month in height increment, and 0.6 mg. per month in dry weight of organic matter.

6. The gross metabolic efficiency was computed and is estimated to be in the neighborhood of 7%.

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686

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On the Previously Undescribed Aggregate Form of the Pelagic Tunicate *Ritteriella picteti* (Apstein) (1904)[1]

LEO D. BERNER[2]

URING MARCH, APRIL, AND MAY, 1949, ver 400 specimens of *Ritteriella picteti* were ken off the west coast of the United ates and Baja California in the net hauls ken by the Scripps Institution of Oceano- aphy in conjunction with the California Co- perative Research Program. This is its first ported occurrence in the eastern Pacific cean and in large numbers. In this material e solitary form and the undescribed aggre- ate form are both represented. The original cognition of the aggregate form was based n specimens that contained embryos of the litary form which were mature enough to ossess their characteristic diagnostic fea- ures. Five individuals of the aggregate gen- ation have been deposited in the United ates National Museum, under number 11170.

I wish to express my appreciation to Dr. artin Johnson for his valuable assistance in e preparation of this manuscript.

In the past *Ritteriella picteti* has been con- dered a rare species by all workers on the haliacea. Apstein (1904: 655) described the ecies from a single specimen taken off Am- oina, Dutch East Indies. He again found the ecies in the Tiefsee Expedition material 906*a:* 252), listing two specimens, but ap- ears to have confused it with *R. amboinensis,* the number may be higher. From the eutsche-Südpolar Expedition, Apstein 906*b:* 168) reported three specimens of *R. cteti.* Ritter (1906: 1–5) took one specimen om Sugura Bay, Japan, which he described a new species, *Cyclosalpa retracta.* Ihle (1910: –46) reported two specimens from the Si- oga collections, and Sewell (1926) reported two specimens from the Indian Ocean collections he examined. Komai (1932: 64–69) and Thompson (1948: 124–126) each reported one specimen from their collections. Thus more than 13 specimens, all of the solitary form, were reported in nearly 50 years of investigation. Thompson (1948: 125) suggested that he may have found the aggregate form of the species, but from his description it appears that he must have been looking at a very young individual or at another species.

Ritteriella picteti (Apstein) (1904)

Cyclosalpa retracta Ritter, 1906
Salpa amboinensis Apstein, 1906*a*
  [non] *S. amboinensis* Apstein, 1904
Salpa picteti Apstein, 1906*a*
Salpa picteti Apstein, 1906*b*
Salpa retracta Ihle, 1910
Salpa picteti Ihle, 1910
Salpa picteti Ihle, 1912
Salpa (*Ritteria*) *picteti* Metcalf, 1918
Salpa (*Ritteria*) *retracta* Metcalf, 1918
Salpa (*Ritteriella*) *picteti* Metcalf, 1919
Salpa (*Ritteriella*) *retracta* Metcalf, 1919
Salpa (*Ritteria*) *picteti* Sewell, 1926.
Salpa (*Ritteriella*) *picteti* Komai, 1932.
Ritteriella picteti Ihle, 1935
Ritteriella picteti Thompson, 1948

DESCRIPTION OF AGGREGATE FORM

Body: (Fig. 1) The body is ovoid, with anterior and posterior processes which are usually short. In dorsal view *R. picteti* is quite similar in appearance to *R. amboinensis, Salpa maxima,* and *S. fusiformis.* The atrial opening is dorsally placed. The test is soft, often collecting debris from the sample, thus making the details of the animals difficult to see. The mature specimens examined have ranged in size from 9 to 35 millimeters, excluding the processes:

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[1] Contribution from Scripps Institution of Oceano- aphy New Series No. 686. Manuscript received June , 1953.

[2] Scripps Institution of Oceanography, University California, La Jolla, California.

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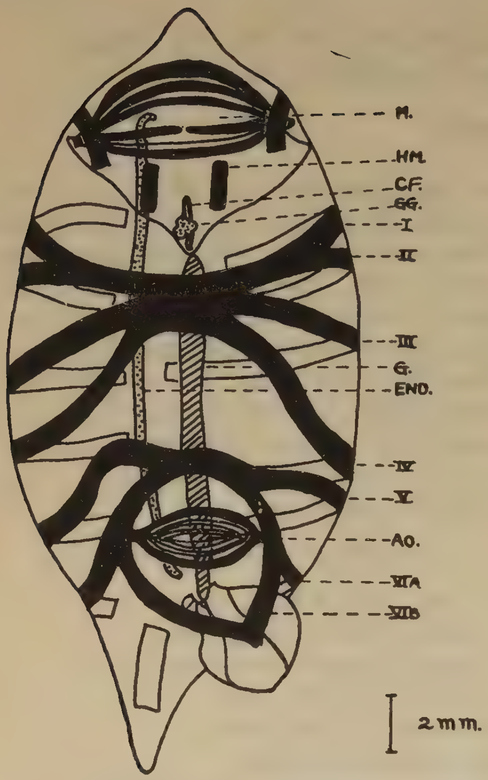

FIG. 1. *Ritteriella picteti*, aggregate form. AO, atrial opening; CF, dorsal tubercle; END, endostyle; G, gill; GG, ganglion; HM, dorsal horizontal muscle; M, mouth; I–VI, body muscles.

Muscles: The body muscles (Figs. 1, 2) may be asymetrically arranged. There are usually six body muscles on each side of the animal although specimens have been found with seven on one side (Fig. 2). Body muscles I and II are joined over the dorsal half of their course, separating laterally, whereas III and IV are joined dorsally over a short portion of their course and contact the bundle formed by muscles I and II in the same general area. Muscles V and VI are also in contact over the dorsal portion of their course. Laterally, muscles IV and V may approach closely. Muscle VI has an anterior branch in front of the gut and a posterior branch which joins its mate from the opposite side over the gut nucleus. There is a broad, independent muscle running along the base of the posterior process. The atrial muscles resemble those of *R. amboinensis*. There are four delicate sphincters attached laterally to a delicate retractor muscle. This muscle then attaches to a heavier retractor which receives the attachment of the heavy basal sphincter. The retractor finally attaches to muscle VI just before the sixth muscle divides. The oral musculature (Fig. 3) includes a single oral retractor laterally on each side and three sphincters on both the upper and lower lips. The sphincters of the upper lip include a wide muscle which is discontinuous medially, U_1, a narrow muscle, U_2, and a wide muscle, U_3. The sphincters of the

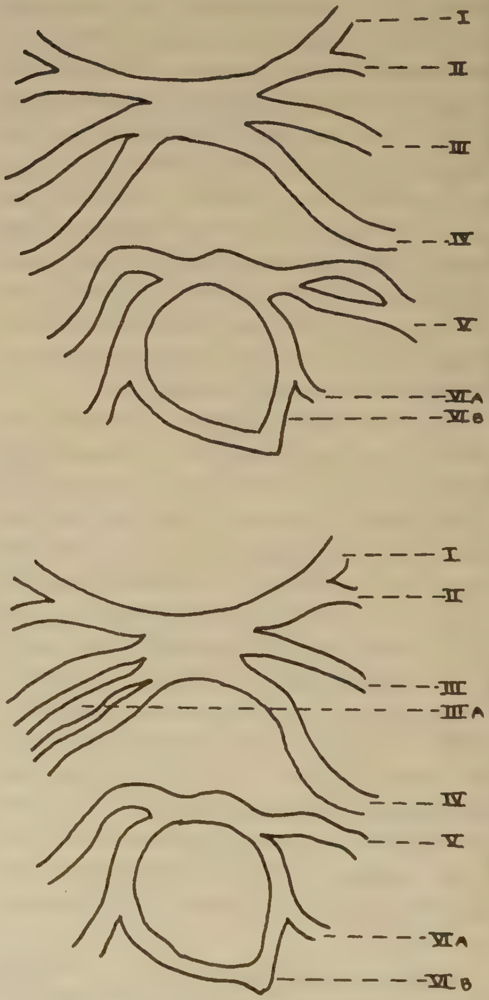

FIG. 2. Diagrammatic representation of some variations found in the arrangement of body muscles of *Ritteriella picteti*, aggregate form: I–VI, body muscles.

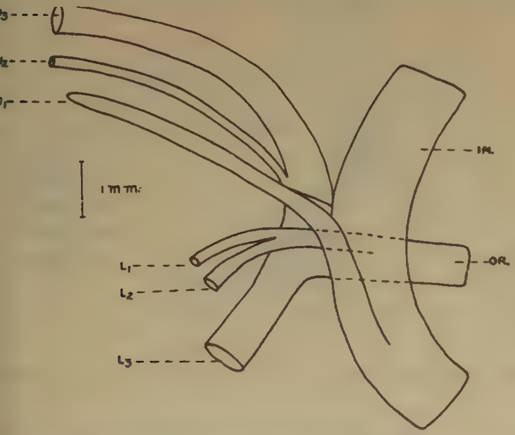

FIG. 3. *Ritteriella picteti*, aggregate from, oral musculature. IM, intermediate muscle; L_1 etc., oral sphincter muscles of the lower lip; OR, oral retractor; U_1 etc., oral sphincter muscles of the upper lip.

ower lip are made up of a narrow muscle, L_1, a wider muscle, L_2, and a wide muscle, L_3. The oral retractor passes internally to the broad intermediate muscle which is discontinuous both dorsally and ventrally. The horizontal muscles are independent and run from the region just behind the last dorsal oral sphincter to about the region between the ends of the first body muscles.

Internal Structure: The gut forms a compact nucleus in which the course of the intestine cannot be clearly traced without dissection. The oesophageal opening, at the base of the gill, is wide and slightly flared. The anal opening is situated on the anterior left side of the gut nucleus. The dorsal tubercle is of typical form, elongate and slightly curved in dorsal view. The dorsal ganglion is much like that figured by Metcalf (1918) for *R. amboinensis*. The endostyle is rather straight, sharply hooked at the anterior end and slightly hooked at the posterior end. It extends from a point below the lower lip to the area posterior to the bifurcation of muscle IV. There is one embryo placed laterally in the area between muscles V and VI.

COMPARISON WITH OTHER SPECIES

In comparing this species with *R. amboinensis*, the other member of the genus, one finds the two very similar. There are certain characteristics, however, that show striking differences; the body muscle bands in *R. picteti* are wider and composed of more fibers. Two typical individuals are compared in the table below.

The large number of fibers in muscle VI of *R. picteti* before its division might indicate that there are in reality two muscles involved and that the posterior branch might be numbered VII. It is felt however that, because of the long-established convention in numbering muscles, the normal order should be maintained even though the muscle might be subdivided. Although the number of muscle fibers is not constant from specimen to specimen, the greater width of muscle bands and greater number of fibers in the specimens of *R. picteti* examined has been a constant feature. This variation in muscle-band width was also observed to a lesser extent in the solitary forms examined. The cross banding on the gill bars of *R. picteti* appears to be more closely spaced than that on the gill bars of *R. amboinensis*. The oral musculature of the two species is quite different, *R. picteti* having three oral sphincters on each lip whereas *R. amboinensis* has only two.

The greatest difficulty encountered has not been in the differentiation of the two *Ritteriella* species but in the differentiation of *R. picteti* from the aggregate form of *Salpa fusiformis*. If the muscle banding is distinct there

TABLE 1
COMPARISON OF THE SPECIES OF RITTERIELLA

BODY MUSCLE	*R. picteti*		*R. amboinensis*	
	Fibers	Width in millimeters	Fibers	Width in millimeters
I	16	0.75	4	0.1
II	16	0.50	5	0.1
III	19	0.50	5	0.1
IV	18	0.50	6	0.1
V	17	0.50	6	0.1
VI	24	0.50	6	0.1
Total length of animal....	11 mm.		9 mm.	

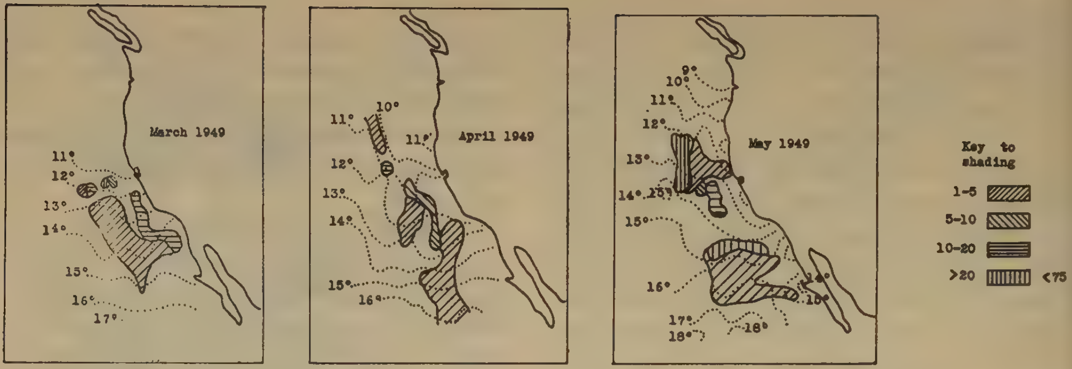

FIG. 4. Charts showing the distribution and approximate numbers of *Ritteriella picteti*, per 1,000 cubic meters of water filtered. Isotherms in degrees centigrade.

is no problem, but in specimens in which the muscles are not easily seen separation of the species is complicated. The best solution to the problem yet found is staining the muscles. For the purpose of this "identification staining," Rose Bengal has been found very useful although not suitable for permanent preparations. A stock solution of 0.1 per cent Rose Bengal may be added to a mixture of sea water and formalin in various amounts to give the intensity of staining desired, with no salt reaction. The main objection to the method is that the stain washes out very easily.

The distribution of *R. picteti* during the period covered by this paper is shown in Figure 4; it can be seen that the occurrence of the species is variable. The patchiness seen is typical of distributions of "salps" and especially true of those which do not occur in large numbers and are not extremely common. This form appears to be much more tolerant of cold water than its relative *R. amboinensis*. It has been taken in water with a temperature as low as 10 degrees at a depth of 10 meters. In the area examined, the lower limit of their range appears to be in the vicinity of this 10-degree isotherm.

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Status and Synonymy of the American Percid Fish Hadropterus scierus*

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There has been much disagreement in regard to the characters, classification, and nomenclature of the American darters described as *Hadropterus scierus* Swain (1883:252), as *H. scierus serrula* Jordan and Gilbert (1886:16), and as *H. maxinkuckiensis* Evermann (1900a:366). The questions involved have therefore been subjected to inquiry.

When we prepared the first draft of this paper more than ten years ago, we planned to present a detailed map and discussion of the distribution of *H. scierus;* to deal with its geographical and speciational relationships with other species, particularly *H. nigrofasciatus;* to treat in detail the geographical variations within *H. scierus;* and to describe a new subspecies from San Marcos River and other parts of the Guadalupe River system in Texas. The last two items have now been handled for the Southwest by Clark Hubbs (1954). The other tasks remaining undone we must leave to others.

ACKNOWLEDGMENTS

For use of material and other cooperation we are indebted to the authorities of the United States National Museum, the Museum of Zoology of the University of Michigan, and the Chicago Natural History Museum. Individuals who have lent us a helping hand include Reeve M. Bailey, J. L. Baughman, Aden C. Bauman, Clark Hubbs, Laura C. Hubbs, Leonard P. Schultz, and Boyd W. Walker.

SERRATED PREOPERCLE AND CLASSIFICATION OF HADROPTERUS SCIERUS

The character of the serrated preopercle, which has been stressed in the separation and classification of *Hadropterus scierus,* is much less distinctive than has often been indicated. This feature was not mentioned by Swain (1883) in the original description of the species, but was pointed out in the next year by Gilbert (1884:205), who gave the "well-developed serration of the preopercle" as the chief character of the new genus *Serraria,* based on Swain's species. Eigenmann and Fordice (1886:411) and Jordan and Gilbert (1886:16) stated that the serrations become obsolete in large adults. In reporting on additional material from Indiana Jordan (1890:165) wrote "preopercle serrulate, at least in young specimens." We find, however, that the serrulations are commonly lacking in the young and tend to become stronger with age (as noted by Meek, 1896:348). Jordan and Evermann (1896a:1037) qualified the character with these statements: "preopercle more or less distinctly serrate, especially in the young and in southern specimens." We find, however, that the range of variation is about the same in the south as in the north, except that the extreme conditions characterize the populations of different streams in Texas. Forbes and Richardson (1909:290) found no serrations in the two half-grown specimens they had from Illinois, and Evermann and Clark (1920:432) detailed the variation in this character, as exhib-

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 687.

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ited by Indiana specimens. Statistical data on the number of serrae in the Southwest and in Indiana are being presented by Clark Hubbs (1954).

The rudimentary serration of the preopercle in a number of darters harks back to an ancestral condition, either directly or as the recrudescence of a character that had been phenotypically suppressed, like the ctenii on the scales of the poeciliid genus *Xenodexia* (Hubbs, 1950:5-7). (In describing the ctenoid scales of *Xenodexia* as unique among cyprinodonts, I forgot that the African lacustrine cyprinodontid genus *Lamprichthys* is similarly though presumably independently endowed. The same evolutionary reasoning probably holds for the origin of the ctenii in both genera, for in this respect each is unique in its family. There is a strong alternative possibility—that *Lamprichthys* is a primitive atherine that has lost its spinous dorsal.—C.L.H.)

The serrulations of the preopercle certainly provides no ground for the generic or even subgeneric separation of *Hadropterus scierus*. In this character *H. scierus* scarcely differs from the genotype of *Hadropterus* (*nigrofasciatus* Agassiz). As Boyd W. Walker pointed out to us, in some series of *nigrofasciatus* most of the half-grown to adult specimens have weak to strong preopercular denticulations. Some of the cotypes of that species have the preopercle serrulate and the type of *Alvordius spillmani,* a synonym, has definite though weak serrations.

H. scierus further agrees with *H. nigrofasciatus* in that the scales of the midventral line, except those between the pelvic fins, are hardly modified in the female and in the adult male are smaller and less spinose than in some other species. This character was not accurately stated and was given undue prominence in Jordan and Evermann's key (1896a:1029-1030).

The close relationship between *H. sciurus* and *H. nigrofasciatus* was appreciated by Swain (1883:252).

The moderate union of the gill-membranes, which led Swain (1883) to question the pertinence of *H. scierus* to the genus *Hadropterus* and which was used by Gilbert (1884:205) as another generic character of *Serraria* is a reasonably good specific character but varies too much intraspecifically as well as interspecifically to be used as a generic or subgeneric criterion. This variation has been shown by relative measurements, such as those presented by Hubbs and Raney (1939:4, Table I).

Typical *H. scierus,* from the Ohio River system in Indiana, Tennessee, and northern Alabama, differs from *H. nigrofasciatus* not only in the somewhat more connected gill-membranes and in coloration (more blotched, less banded), but also in having, on the average, more rays in the dorsal and anal fins (table 1). In Texas this distinction breaks down, for the new subspecies of the Guadalupe River system has an intermediate average number and other Texas races of *scierus* seem to agree with *nigrofasciatus* in this respect.

Both species occur, sometimes together, in the central part of the Gulf lowland, where their morphological and ecological relationships remain to be worked out. Since no indication of intergradation was observed, the species appear to be distinct.

STATUS OF THE NOMINAL TEXAS SUBSPECIES, SERRULA

The collections of this species from Texas have been referred to a distinct subspecies, *Hadropterus scierus serrula* Jordan and Gilbert (1886:16), with

TABLE 1.—Total number of dorsal plus anal rays in *Hadropterus nigrofasciatus* and in *H. scierus*

Species and State	Total number of dorsal plus anal rays									
	31	32	33	34	35	36	37	38	39	Aver.
H. nigrofasciatus										
Florida	....	....	5	8	3	1	....	....	....	34.0
Georgia	1	2	4	7	3	....	....	....	....	33.5
Alabama (cotypes)	....	....	1	1	1	....	....	....	....	34.0
Mississippi	....	1	2	8	5	2	1	....	....	34.4
H. scierus										
Indiana	....	....	....	....	2	4	3	4	....	36.7
Tennessee and N. Alabama	....	....	....	....	5	5	6	3	3	36.7
Texas, N. of Guadalupe R.	....	1	2	1	2	1	....	....	....	34.0
Texas, Guadalupe and San Marcos rivers	....	....	....	....	4	4	1	....	....	35.7

the following original characterization, repeated by Jordan and Evermann (1896a:1038) and other authors:

> Abundant. The Texas specimens of this species differ somewhat from those examined from Indiana and Arkansas, and may be taken as a distinct variety (*serrula*). The scales are somewhat smaller in variety *serrula* (lat. l. 68 to 71 in *serrula;* 64 to 66 in most Indiana examples). The coloration in *serrula* is paler, with more sharply-defined markings, the black blotches on the side being less confluent, and the sides of the belly without dark clouds.
>
> In the Texas specimens the breast is naked, while in most Indiana examples it is more or less scaly. The preopercle is very weakly, but generally distinctly serrulate.
>
> In very old specimens from Indiana these serrations disappear.

There is apparently some local variation in the number of scales, but neither in published counts (table 2) nor in original determinations (table 3) do we find grounds for the recognition of a fine-scaled Texas subspecies (except in that, on the average, the subspecies being named from the Guadalupe River system has more scales than other Texas races and slightly more than in typical northern *scierus*). The paler coloration attributed to the types of *serrula* was probably due to their having been taken in less clear water (specimens from the crystal waters of San Marcos River are very boldly marked). The degree of fusion of the lateral blotches is subject to much variation, as in other species of the genus, but with no apparent geographic trend.

TABLE 2.—Published scale counts for *Hadropterus scierus*

State	Scales	Reference	Identification (as given)
Indiana	65	Swain, 1883:252	*H. scierus*
Indiana	64-66	Jordan and Gilbert, 1886:16	*H. scierus*
Indiana	68	Jordan, 1890:160	*H. scierum*
Indiana	62-69	Evermann and Clark, 1920:434	*H. scierus*
Illinois	64-67	Forbes and Richardson, 1909:290	*H. scierus*
General	68-70 (scales), 64-71 (pores)	Jordan and Evermann, 1896a:1037	*H. scierus*
General	64-66	Jordan and Evermann, 1896a:1038	*H. scierus*
Arkansas	68-73	Meek, 1896:348	*H. scierum*
Texas	68-71	Jordan and Gilbert, 1886:16, and Jordan and Evermann, 1896a:1038	*H. scierus serrula*

The blotching of the lower sides is often developed in adult females, at various localities. In all regions scales more or less cover the posterior half of the breast, especially toward the sides, and the anteromedian part of the breast is typically scaleless. The breast varies from wholly scaleless to com-

TABLE 3.—Original scale counts for *Hadropterus scierus*

	Number of scales in lateral-line series																		
River and State	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	Aver.
Ohio R., Ohio and Kentucky	....	....	....	....	....	....	....	....	....	2	....	1	1	4	....	....	....	....	67.6
Indiana and Illinois*	1	1	1	4	6	11	11	10	8	14	8	7	5	2	3	2	....	....	63.8
Tennessee, Alabama, and Georgia	....	1	1	2	2	1	2	2	2	1	3	....	2	....	....	....	....	....	62.7
Mississippi R., Missouri	....	....	....	....	....	....	....	....	1	....	....	....	....	....	....	....	....	....	64?
St. Francis R., Arkansas	....	....	....	....	....	....	....	2	....	1	1	....	1	1	1	1	....	1	67.6
Arkansas R., Oklahoma	....	....	....	1	1	2	1	2	2	1	1	1	....	....	....	....	....	....	62.9
Red R., Arkansas	....	....	....	....	....	....	....	....	....	1	1	....	1	....	1	1	....	....	68.0
Sabine R., Texas	....	....	....	....	....	....	1	1	1	2	....	....	....	....	....	....	....	....	63.8
Neches R., Texas	....	....	....	....	....	....	....	....	1	....	....	....	....	....	....	....	....	....	64?
Trinity R., Texas	....	....	....	1	....	....	1	2	1	2	2	....	1	....	....	....	....	....	64.1
Buffalo Bayou and San Jacinto R., Texas	....	....	....	1	....	2	1	1	3	....	1	....	....	....	....	....	....	....	62.7
Lampasas R., Texas	....	....	....	....	7	4	5	11	7	2	4	1	....	....	....	....	....	....	62.8
San Marcos R., Texas	....	....	....	....	....	....	....	2	2	3	5	5	2	1	3	1	1	....	66.9
Guadalupe R., Texas**	....	....	....	....	....	....	....	....	....	1	1	3	....	4	1	1	....	....	68.1

* Only one from Illinois (Grand Pierre Creek), with 66 scales.
** From New Braunfels.

pletely scaled, but the extreme conditions seem rare everywhere. As previously mentioned, we find no marked geographical consistency in the degree of serration of the preopercle (except locally in Texas).

It is concluded that *Hadropterus scierus serrula* was not established on valid grounds (this view was indirectly indicated, in the statement of the range by Meek, 1894a:271 and by Pratt, 1935:119). Preliminary studies indicate tendencies toward local differentiation, but these appear too indefinite to be used now for the recognition of subspecies, other than the Guadalupe form. A more intensive study, based on an abundance of fresh material from throughout the wide range of the species, however, may lead to the conclusion that *Hadropterus scierus,* like many other darters, is a complex of local subspecies. The critical variational study being published by Clark Hubbs gives some basis for the separation of *serrula,* but since the work was largely confined to the Southwest, the author has refrained from recognizing any subspecies other than *H. s. scierus* and the Guadalupe form.

Since a subspecies *serrula* may eventually be recognized, it is desirable to fix the type locality. In the original account (1886) Jordan and Gilbert were equivocal in designating the type specimens. On page 16, in the section on "Sabine River at Longview, Texas" they made the following statement, under "*Hadropterus scierus* Swain, var. *serrula,* var. nov. (36481.)": "The Texas specimens of this species differ somewhat from those examined from Indiana and Arkansas, and may be taken as a distinct variety (*serrula*)." The characters thereupon assigned (see above) were taken from different lots. The smaller scales apply to the Guadalupe subspecies, whereas the "very weakly, but generally distinctly serrulate" preopercle best characterizes the material from Longview. Under "Trinity River, at Dallas, Texas" and "Rio Lampasas, at Belton, Texas," there are respectively listed (pp. 17-18), with ecological notes only, "*Hadropterus sicerus serrula* Jordan & Gilbert. (36476.)" and "*Hadropterus scierus* Swain (*serrula*)." The Rio Lampasas examples are labelled *H. scierus,* whereas those from the Trinity bear an unpublished manuscript name, but neither set is accompanied by an original label. The San Marcos specimens bear the same manuscript name, in Jordan's hand. Obviously, Jordan and Gilbert regarded all their Texas material as types of a form which they named *serrula* in the 1886 paper, but which, in fact, represents at least two subspecies. The restriction of the type locality seemingly was left to a subsequent author, apparently Evermann and Kendall (1894:88 and 113), who selected the Sabine River at Longview. Jordan and Evermann (1896a:1038 and 1896b:359) without warrant designated the type locality and type series as follows: "Jordan and Gilbert, Proc. U. S. Nat. Mus., 1886, 16, Red River, Fulton, Arkansas (Type, No. 36481. Coll. Jordan & Swain)." But Jordan and Gilbert did not collect the subspecies in Red River and No. 36481 came from the Sabine River. The heading for that river, set somewhat obscurely at the top of page 15, was obviously overlooked. (This slip was responsible for the inclusion by Jordan and Evermann of southern Arkansas in the range of *serrula.*) Hoping to remove doubt as to the validity of the type designation and type locality of *Hadropterus scierus serrula,* we hereby designate the series of specimens from the Sabine River at Longview, Texas (Cat. No. 36481, U. S. N. M.) as the sole lectocotypes. This action clears the way for the recognition of the Guadalupe subspecies and for the possible eventual recognition of a subspecies from the Brazos River system, where the preopercular serrations appear to be more strongly developed than elsewhere. Other local characteristics of the Southwestern populations, particularly in proportions, are stressed by Clark Hubbs (1954).

SYNONYMY OF THE DUSKY DARTER

The following synonymy is designed to trace the complete nomenclatorial history of the species. It includes the references that pertain to the new subspecies being named from the Guadalupe River system in Texas (Clark Hubbs, 1954).

HADROPTERUS SCIERUS Swain

Hadropterus scierus.—Swain, 1883:252 (orig. desc.; close to *H. nigrofasciatus;* Bean Blossom Cr., Ind.). Jordan, 1885:867 (*Serraria* recognized as a subgenus). Jordan and Eigenman, 1885:69 (skeletal char.). Eigenmann and Fordice, 1886:411 (serrulations on preopercle obsolete in large adults). Jordan and Gilbert, 1886:13 (Washita [Ouachita] R. near Arkadelphia and Saline R. near Benton, Ark.; like Ind. specimens). Jordan and Evermann, 1896a:1020, 1037-1038 (desc.; range; syn.); 1896b:359 (range); 1900:3268, pl. 167, fig. 441 (Clinch R. at Walkers Ford, Tenn.). Evermann, 1900a:364-367 and 1900b:452 (Ind. records; *H. maxinkuckiensis* [erroneously] considered a local derivative). Osburn, 1901:92 (desc.; dist. in Ohio; Ohio R. near Little Sandy R.). Large, 1902:27 (char.; Skillet Fk., Wayne Co., Ill.). Eigenmann and Beeson, 1905:152 and Meek, 1908:170 (Ind. rec.). Forbes, 1909:389, 400 (dist., in Ill.). Forbes and Richardson, 1909 (and 1920):289-290, fig. 60 (desc.; Embarrass R., Ill.). Cockerell, 1913:154 (scale char.; Tippecanoe R., Marshland, Ind.). Hankinson, 1913:52 (Embarrass R. near Charleston, Ill.). Evermann and Hildebrand, 1916:449 (Clinch R., Tenn.). Evermann, 1918:321, 326, 355, 367 (rec. and dist., Ky. and Tenn.). Evermann and Clark, 1920:432-437 (Outlet Cr. below Lost L., Ind.; desc.; status *re H. aspro* and *H. maxinkuckiensis*). Pratt, 1923:124, 126 (diag.; range). Osburn, Wickliff, and Trautman, 1930:175 and Wickliff and Trautman, 1934:3 and 1937:3 (Ohio). Hubbs, 1946:38 (Okla.). Schrenkeisen, 1938:216-217 (desc.; range; relations). Trautman, 1940:29 (in key; Pike, Vinton, Jackson, and Gallia counties, Ohio; ecol.). Brind, 1941:65 (comp.). Lamb, 1941:45 (rec., San Jacinto R. system, Tex.). Baughmann, 1950:247 (Tex.). Moore and Rigney, 1952:11 (associated species; Blue R., Okla.). Moore, 1952:[10] (Okla.). Cross and Moore, 1952:407 (rec., Poteau R. syst., Okla. and Ark.). Hubbs, Kuehne, and Ball, 1953:237, fig. 20 (records mapped, upper Guadalupe R. syst., Tex.; subsp. undescribed).

Serraria sciera.—Gilbert, 1884:205 (desc.; type of new genus; Salt Cr., Ind.). Jordan, 1929:161 (desc.; range). Jordan, Evermann, and Clark, 1930:284 (range). ODonnell, 1935:489 (Embarrass R. near Charleston, Ill.). Pratt, 1935:119 (diag.; northern Ind. to Tenn. and Tex.). Blatchley, 1938:88 (char.; Ind. rec.; *H. maxinkuckiensis* a prob. var. [error]). Driver, 1942:284 and 1950:297 (char. in key; Ind. to Tex.).

Etheostoma scierum.—Evermann and Jenkins, 1888a:51, 54 and 1888b:119, 122, 123 (Ind. rec.). Jordan, 1888 (and 1890 to 1916):127-128 (desc.; range). Henshall, 1889:126 (Ohio R. near Little Sandy R.). Jordan, 1890:160, 164-165, 167 (char.; Ind. rec.). Gilbert, 1891:151-152 (Spring Cr., Courtland, Ala.). Woolman, 1892:260, 286, 288 (Ky. rec.). Hay, 1894:276 (desc.; Ind. rec.). Eigenmann and Beeson, 1894a:103-104 and 1894b:61 (Ind. rec.). Meek, 1894a:271 and 1894b:90-93 (Ark. ref.). Boulenger, 1895:80-81 (syn.; desc.; Bean Blossom Cr., Ind.). Meek, 1896:348 (Big Bay and Marked Tree, Ark.).

Hadropterus scieurus (misspelling).—Blatchley, 1901:257 (*H. maxinkuckiensis* prob. a var. [error]; Ind. rec.).

Hadropterus sciurus (misspelling).—Fowler, 1945:375 (specimens from San Marcos, Tex., differing from fig. of *H. "sciurus"* in physiognomy and color).

Hadropterus scierus scierus.—Shoup, Peyton, and Gentry, 1941:70, 73 (rec., Wolf and Obey rivers, Tenn.). Trautman, 1946:39 (in key; Pike, Vinton, Jackson, and Gallia counties, Ohio; ecol.). Gerking, 1946:85, 1 map (dist., rec., and ecol., Ind. [excluding rec. for L. Maxinkuckee]).

Hadropterus scierus serrula.—Jordan and Gilbert, 1886:16, 17, 19, 23, 24 (orig. diag.; Tex. rec.). Jordan and Evermann, 1896a:1038 (diag.; southern Ark. [error] through eastern Tex.); 1896b:359 (range repeated). Schrenkeisen, 1938:217 (color char.).

Etheostoma scierum serrula.—Jordan, 1888 (and 1890 to 1916):128 (char.). Evermann and Kendall, 1894:81, 84, 88, 93, 113 (rec. and dist. in Tex.). Evermann, 1918:321 (Bull Run, Hershells, Tenn.). Parks, Cory, and others, 1938:22 (Big Thicket area, east Tex.).

Hadropterus serrula.—Fowler, 1933:62 (Clear Cr., Reeves, La.).

Serraria sciera serrula.—Jordan, 1929:161 (char.).

Serraria serrula.—Jordan, Evermann, and Clark, 1930:284 (range).

STATUS OF HADROPTERUS MAXINKUCKIENSIS

A supposedly close relative and local representative of *Hadropterus scierus* was described from an inlet of Lake Maxinkuckee in Indiana by Evermann (1900a:366-367, pl. 17, lower fig.), under the name of *Hadropterus maxinkuckiensis.* This account was repeated, with modifications, by Evermann (1900b:452), Jordan and Evermann (1900:3166-3167), and Evermann and Clark (1920:435-437, 1 fig.). The nominal species was listed as distinct by Jordan, Evermann, and Clark (1930:284) under the name of *Alvordius maxinkuckiensis.* Holding to the name *Hadropterus maxinkuckiensis,* Blatchley (1901:257 and 1938:88, 1 fig.) regarded this nominal form as probably a variety of *H. scierus,* and Schrenkeisen (1938:217) has recently repeated Evermann's characterization. Fowler (1945:375) synonymized *H. maxinkuckiensis* with "*H. sciurus.*" Gerking (1945:map 78) included a Lake Maxinkuckee record on his map for *H. s. scierus.*

An examination of the type specimen, description, and figure, however, suffices to show that *Hadropterus maxinkuckiensis* was based on a specimen of *Hadropterus maculatus* Girard (on the status of *H. maculatus* refer to Hubbs, 1926:59-60). In the color of the head, body, and fins, and particularly of the caudal base, as well as in the smooth preopercle and free gill-membranes, the type of *maxinkuckiensis* agrees with *H. maculatus* and differs from *H. scierus.* The scales are larger than usual in either species, but within the range of variation exhibited by each. The union of the dorsal fins and the large mouth in the type of *H. maxinkuckiensis* also fit into the limits of variation known for *H. maculatus.* That species shows much fluctuation in color pattern (but to date has defied analysis into subspecies). Consequently, *H. maxinkuckiensis* is to be relegated to the simple synonymy of *H. maculatus.*

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A New Texas Subspecies, apristis, of the Darter Hadropterus scierus, with a Discussion of Variation Within the Species

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In this paper a new subspecies of darter from Texas is described, its ecology is discussed briefly, and a study is presented of the geographical variation exhibited by *Hadropterus scierus,* especially in Texas and Oklahoma.

Description of a New Subspecies of Darter from Texas

During the past two decades a number of Texas freshwater fishes have been recognized as meriting new taxonomic ranking. Recently four of these fishes have been named (Hubbs, 1951, and Hubbs and Bonham, 1951). In this paper a continuation of the series, a new darter is defined.

The methods of counting and measuring used in this investigation are those proposed by Hubbs and Lagler (1947). The variational data are expressed by a simplified graphical scheme that follows the Hubbs and Perlmutter (1942) modification of the method proposed by Dice and Leraas (1936). In each unit of the graphs the extreme range is represented by the base line, the mean by the vertical line, two standard errors on each side of the mean by the solid area, and one standard deviation on each side of the mean by the outlined area. This further modification of the Dice and Leraas method for the graphical comparison of series of samples was developed jointly with Carl L. Hubbs and is discussed in another paper (Hubbs and Hubbs, 1953).

The status and synonymy of the species *Hadropterus scierus* is being treated by Hubbs and Black (1954).

Acknowledgements

Drs. Carl L. Hubbs, John D. Black, and Reeve M. Bailey, all who had, either jointly or separately, prepared manuscripts to describe this form, kindly dropped their plans in favor of this paper. Drs. Bailey and Hubbs contributed helpful suggestions during the preparation of the manuscript. From the collections of the University of Michigan Museum of Zoology Dr. Bailey made available all Indiana specimens used in this study and many from scattered localities throughout Texas. Dr. George A. Moore provided the Oklahoma specimens studied. Mr. Kenneth C. Jurgens, Mr. Robert J. Kemp, Mr. R. Kirk Strawn, and Prof. Frank T. Knapp secured specimens from Texas. Mr. Marion Toole kindly gave permission for the author and his students to make numerous collections throughout Texas.

Hadropterus scierus apristis Carl L. Hubbs and Clark Hubbs n. subsp.—Guadalupe Dusky Darter

Hadropterus scierus serrula Jordan and Gilbert, 1886:23-24 (San Marcos and New Braunfels records). Jordan and Evermann, 1896:359 (same records). *Etheostoma scierum serrula* Evermann and Kendall, 1894:113-114 (San Marcos and New Braunfels records). *Serraria serrula* Jordan, Evermann, and Clark, 1930:284 (in part). *Hadropterus scierus* Baughman, 1950:247 (in part). Hubbs, Kuehne, and Ball, 1953:237. *Hadropterus sciurus* (misspelling) Fowler, 1945:375 (San Marcos specimens).

Diagnosis.—The preopercular serrae number 0 to 1, rarely 2 to 6. Fin rays: dorsal X to XIV (usually XI to XIII)-11 to 13 (rarely with one spine in front of soft dorsal rays); anal II (rarely I), 7 to 10 (usually 8 or 9); caudal 15 to 17; pectorals 13 to 15 (rarely 12); pelvics I, 5. Scales: lateral-line 63 to 78 (usually 66 to 72); rows from dorsal to lateral line 8 to 10. Branchiostegals 6. Gill-rakers 1+9.

The mouth is inferior and oblique. The frenum is broad and without a groove. The upper jaw extends to a point below the most anterior part of the eye. The moderate eye, which approximately equals the snout and upper jaw lengths, barely reaches the dorsal profile. The jaws bear an outer row of enlarged teeth and an inner band of smaller teeth. Those forming a patch on the vomer and a row on each palatine are of the smaller size. The distance from the insertion of the pelvic fin to the union of the gill-membranes is contained 0.7 to 1.1 times in the distance from the union of the gill-membranes to the tip of the mandible (larger figures for smaller specimens). Eye length contained 1.8 to 2.2 times in distance from union of gill-membranes to tip of mandible (larger figures for larger specimens).

The profile rises gently from the rounded snout to the first dorsal spine, except for a slight hump at the nape. It remains more or less straight along the spinous dorsal and starts to decline to the level caudal peduncle either at the beginning or middle of the soft dorsal.

Except for the shorter last one or two, the dorsal spines are all of approximately the same length. The dorsal soft-rays are all longer than the spines and all, excepting the shorter ones at each end, are of approximately the same length. The two dorsal fins vary from distinctly to barely separated. The caudal is bluntly emarginate.

The first anal spine is much thicker than the second, which is similar to the dorsal spines. The anal soft-rays are all approximately twice as long as the spines.

The bluntly pointed pelvics extend two thirds of the distance to the anus; the rounded pectorals, three fifths of the distance to the anus.

Scales cover the body except the anterior part of the belly and most of the pectoral base (there are some embedded scales on the ventral part of the pectoral base). The row of enlarged and strongly ctenoid scales along the midline of the belly of males, separated from normal scales by a series of intermediate scales, is most pronounced during the breeding season. In females and immature males these scales are less modified. The dorsals, anal, pelvics, pectorals, and the distal two thirds of the caudal are naked. Several parts of the head are scaled: the opercle is covered with imbricate scales; scattered embedded scales are present on the side of the head above the opercle; the cheek has imbricate scales above a line between the lower edge of the pupil and the upper pectoral ray; and embedded scales occupy the lower cheek.

The color pattern of *Hadropterus scierus* in general and of *H. s. apristis* in particular exhibits relatively little sexual dimorphism or seasonal variation. The ground color is olive, with seven distinct rectangular black blocks along the midline (an additional indistinct one above the pectoral base and at the caudal base). The blocks are connected to eight indistinct gray saddles. The blocks are separated by an equal distance of ground color in females but are almost connected in males. Three dark spots are on the caudal base: the upper almost meets its opposite number across the procurrent rays; the middle is at the end of the lateral line; and the lower is about midway between the middle spot and the ventral surface. The middle and lower spots are often fused to the last body block, forming its darker posterior border. On the head an anterior continuation of the series of blocks forms an irregular line through the eye. The proximal half of the spinous dorsal is black in males and gray in females, and depending upon the season the distal part is yellow to orange in males and clear to yellow in females. The other median fins have gray marks on the rays that in combination form irregular bars. The paired fins vary from gray in breeding season to clear in other seasons.

Comparisons.—This and the other subspecies of *H. scierus* can be distinguished easily from their near relatives in Texas. *Hadropterus maculatus* has a longer upper jaw (nine percent of the standard length as compared with eight percent or less in *H. scierus*), no scales on the nape (extralimital *maculatus* may have the nape scaled), and a distinct roundish median black spot at the base of the caudal. *Hadropterus* (*Imostoma*) *shumardi*? has fewer scales (around 50 instead of 60 or more), a narrow frenum, and elongate tuberculate anal rays in the mature male.

The major part of the diagnosis of *H. scierus apristis* would fit not only this subspecies, but also the other races of *H. scierus*. The distinctions are brought out in the following comparison and in the tabulations discussed under racial variation. The most significant and consistent difference lies in the number of preopercular serrae (left side only counted). The counts for *apristis* are approached only by those of the Arkansas River specimens (fig. 1), among the series investigated. Although the rays of the median fins of *apristis* are shorter on the average than those of most other populations, the rays of the paired fins usually are longer. The dark rectangular blocks on the side are longer and narrower than in other races. The narrow bars that connect the dark blocks in typical *scierus* are reduced or absent in *apristis*.

Range, habitat, and abundance.—Hadropterus scierus apristis occupies all suitable habitats in the San Marcos and Comal rivers, except those around the spring heads. It has also been collected in the Guadalupe River, but no specimens have been taken west of Kerrville, despite the very extensive collecting reported on by Hubbs, Kuehne, and Ball (1953). It has never been taken in any tributary to the rivers named above. There are no specimens in the few collections available from the San Antonio River System.

The Guadalupe dusky darter is a riffle fish. It is most commonly found under or around ten- to twelve-inch boulders in the main current. It appears to prefer moderately turbid water, for it is absent from the clearest waters tributary to the Guadalupe, namely the spring heads and main river west of Kerrville, and it has been found most commonly east of the Balcones Escarpment, where water turbidity is high. It has never been obtained from a stream that is not permanent.

MATERIAL EXAMINED

The material on which this paper is based is deposited in the University of Michigan Museum of Zoology (UMMZ), United States National Museum (USNM), Chicago Natural History Museum (CNHM), Oklahoma Agriculture and Mechanical College (OAM), Texas Agriculture and Mechanical College (TAMC), Stanford Natural History Museum (SU), and Texas Natural History Collection (TNHC).

The holotype (UMMZ 162377) and 41 paratypes (UMMZ 162378) were collected by Kenneth C. Jurgens and Robert C. MacEwan from the San Marcos River, one half mile southeast of Prairie Lea, Caldwell County, Texas, on February 11, 1950. Eighty-nine other specimens from the San Marcos River are designated as paratypes (UMMZ 162374, USNM 160628 and 160629, CNHM 46195, OAM 4707, TAMC 1F-13-g-4 and 1F-13-g-10, SU 17311, and TNHC 90 and 501). Two specimens from the Guadalupe River (TNHC 162 and 314) are also designated as paratypes. The type series comprises the San Marcos sample in the racial discussion. Seventy-one specimens from the upper Guadalupe River are not designated as paratypes because they differ in minor ways from the San Marcos individuals. These specimens make up the Hill Guadalupe sample.

Comparative material is listed according to the groupings utilized in the racial study: Colorado River System, Texas, 12 specimens (UMMZ 129788 and 162376, USNM 160627, OAM 4702, and TNHC 1087, 1122, and 1416); Brazos River System, Texas, 49 (UMMZ 110528, 129776, 129895, and 162373, and TNHC 694 and 1024); San Jacinto River System, Texas, 57 (UMMZ 131158, USNM 160616, and TNHC 693 and 1583); Trinity River System, Texas, 58 (UMMZ 162371, CNHM 46196, SU 17313, and OAM 4703); Neches River System, Texas, 22 (UMMZ 162370, USNM 160615, CNHM 46195, OAM 4706, TAMC 1F-13-g-11, SU 17312, and TNHC 383 and 557); Sabine River System, Texas, 39 (UMMZ 162375, USNM 160614, OAM 4705, and TNHC 1521 and 1536); lower Red River System, Texas and Oklahoma, 12 (OAM 4686 and TNHC 1418 and 1458); upper Red River System, Oklahoma, 32 (OAM 1495, 1624, 2900, and 4103); Little River, Oklahoma, 50 (OAM 2878); Arkansas River System, Oklahoma and Arkansas, 26 (OAM 999, 1180, 1230, and 4546); and Wabash River System, Indiana, 19 (UMMZ 81345, 81386, and 113552).

RACIAL ANALYSIS OF HADROPTERUS SCIERUS IN TEXAS AND OKLAHOMA

Many of the proportional measurements used vary with specimen size. Each character was checked for such variation. For the two proportions used that show marked age changes, the pectoral fin length and the upper jaw length, a constant was calculated that makes all the data approximately comparable (see legends for figs. 5, 7).

The specimens utilized in this study were collected at many localities (fig. 2). To increase the statistical validity, the collections are grouped according to stream system and, when adequate numbers of specimens are available (for the Guadalupe and the Red systems) they are grouped within a given system in subdivisions having the same general ecologic conditions. Some variation undoubtedly is obscured by grouping the collections, but this seems preferable to having too many very small samples and is justifiable on other grounds. The San Marcos, Sabine, and Wabash samples include specimens from, or near, the type localities of the three nominal subspecies, *apristis* Hubbs and Hubbs, *serrula* Jordan and Gilbert, and *scierus* Swain.

When the samples are compared graphically, three major groupings by stream systems appear: (1) Hill Guadalupe and San Marcos (*apristis* Hubbs and Hubbs); (2) Colorado, Brazos, San Jacinto, Trinity, Neches, Sabine, Lower Red, Upper Red, and Little; and (3) Wabash. In several respects the fish from the Arkansas River System are intermediate between those of morphologic types (2) and (3); in other ways they are somewhat distinctive. The Lower Red, Upper Red, and Little samples, although considered as type two, approach type three in several characters.

The *apristis* specimens have the fewest preopercular serrae (fig. 1). The lower limits of the standard deviation bars of all other samples except that from the Arkansas River System are separated from the upper limits of the standard deviation bars for *apristis* by a distance greater than one standard deviation. Although the Arkansas sample approaches *apristis* in number of preocular serrae, it is obviously distinct. There is no overlap between its standard deviation bar and that of either *apristis* sample in the caudal peduncle depth (fig. 3), caudal peduncle length (fig. 4), and pectoral length (fig. 5).

The greater length of the *apristis* pectoral fin is of statistical significance when compared with that of all other samples (fig. 5), though subspecific separation could not be based on this distinction alone.

The number of lateral-line scales of the Guadalupe dusky darter is statistically greater than that of any other population except that from the

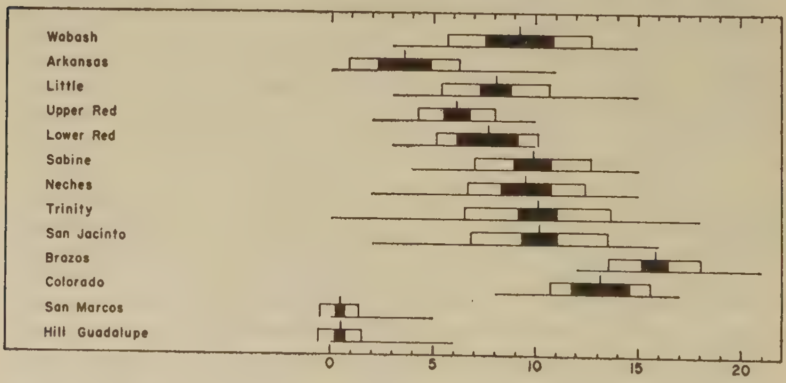

Fig. 1.—Number of preopercular serrae (left side only)

Little River (fig. 6), but again the overlap in counts is too wide for subspecific differentiation on this account.

It is possible that *apristis* may be specifically distinct from *scierus*. In distribution it is extreme (toward the southwest) and it is completely separated from the nearest population of other forms. The waters of the Colorado and

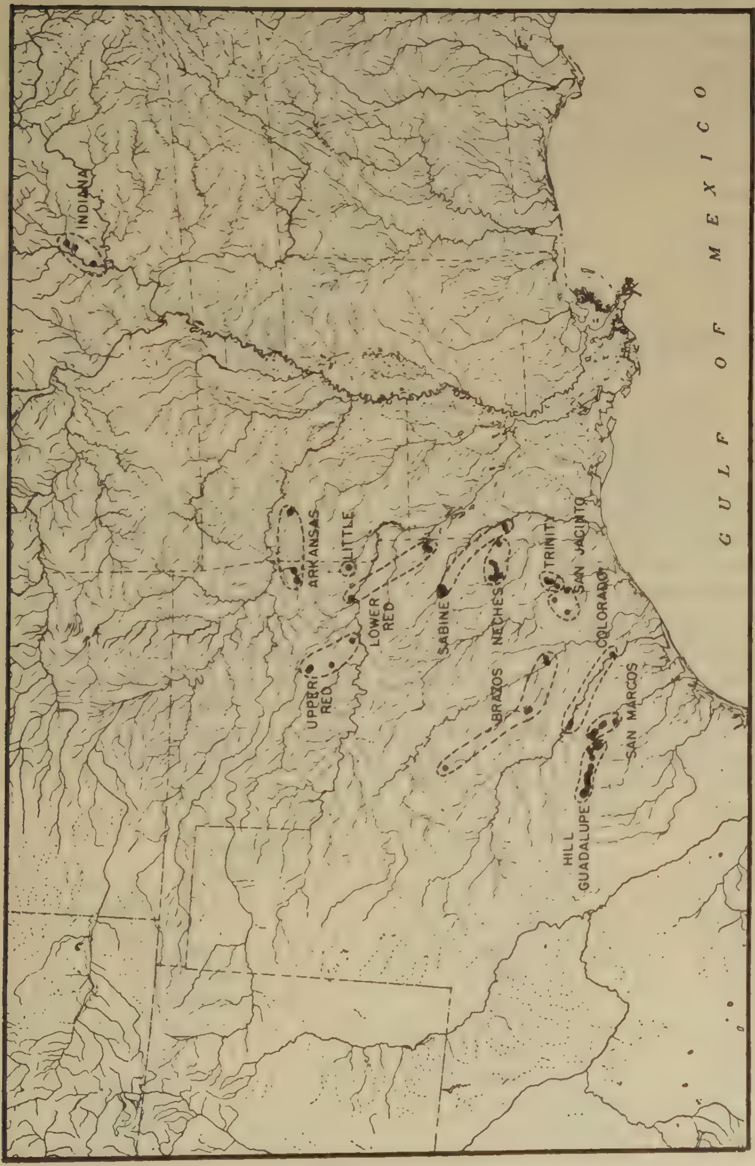
INDIANA
ARKANSAS
LITTLE
LOWER RED
UPPER RED
SABINE
NECHES
BRAZOS
TRINITY
SAN JACINTO
COLORADO
SAN MARCOS
HILL
GUADALUPE
GULF OF MEXICO

Fig. 2—Map of collection localities

Guadalupe rivers empty into the saline coastal water of Texas 50 miles apart. The fact that the populations geographically closest to the Guadalupe River often differ greatly morphologically from those of the Guadalupe River indicates that these populations may be specifically differentiated The difference is especially notable in the number of preopercular serrae (fig. 1), in which character there appears to be no overlap between the two stocks. In fact the series of races from the Arkansas River System to the stream systems just north of the Guadalupe appears to be characterized by a cline that leads away from *apristis.* The Brazos and Colorado samples have the serrae better developed than in any other race of *scierus,* whereas *apristis* has the serrae least developed. The Colorado sample likewise contrasts with the *apristis* samples in pectoral length (fig. 5). Because of the considerable overlap in diagnostic characters when all races are considered, however, the Guadalupe race is considered to be only subspecifically distinct. The question of specific or subspecific rank may be solved when proposed fertility tests have been completed.

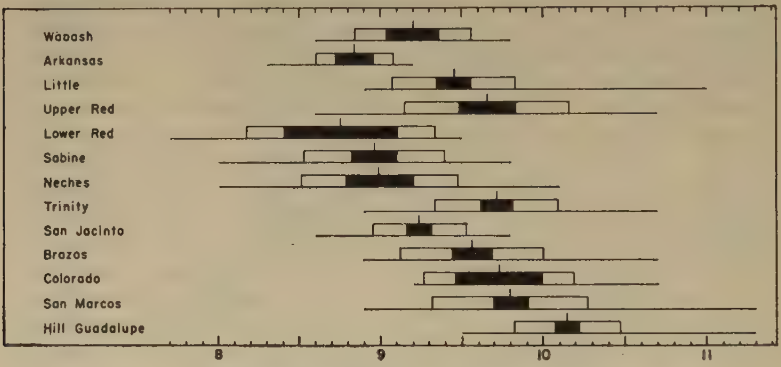

Fig. 3.—Caudal peduncle depth in hundredths of standard length

The specimens of morphologic type three (typical *scierus*) have the shortest upper jaw (fig. 7). When the tabular data are compared, the standard deviation of the Wabash sample overlaps only with that of the specimens from the Arkansas River system, which in this respect are intermediate.

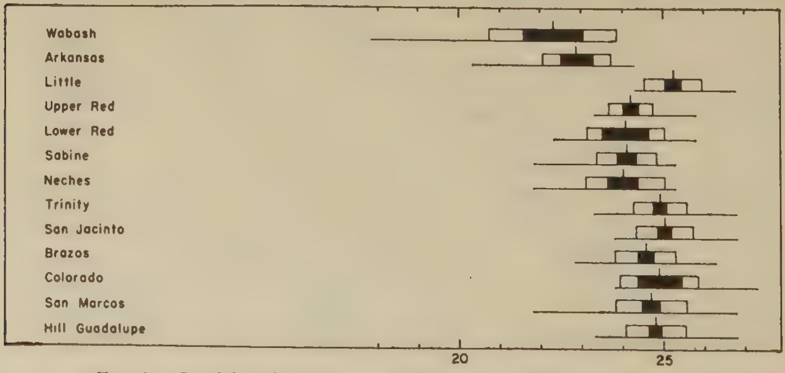

Fig. 4.—Caudal peduncle length in hundredths of standard length

The average snout length of the Wabash sample is the shortest of any studied (fig. 8). This distinction is statistically reliable for the comparisons of the Wabash race with all other samples except the three northernmost (Arkansas, Little, and Upper Red). The fishes from these three localities show definite type three characteristics, *i. e.*, each can be separated statistically (though not subspecifically) from the nine longer-snouted southern samples.

The Wabash specimens have the shortest pectoral fins (fig. 5). When the proportional data are plotted, the standard deviation bar of the Wabash sample overlaps those of the Arkansas, Little, Lower Red, Colorado, Upper Red, and Trinity samples. The overlap with the latter two is very slight, and their average pectoral length approximates that of the non-overlapping samples. The Colorado River System sample is small (twelve specimens) and as it is from a river that is far from Indiana, its similarity to the Indiana specimens in this character may be attributed to sampling error or to independent modification. The three remaining samples (Arkansas, Little, and Lower Red) are intermediate in this respect.

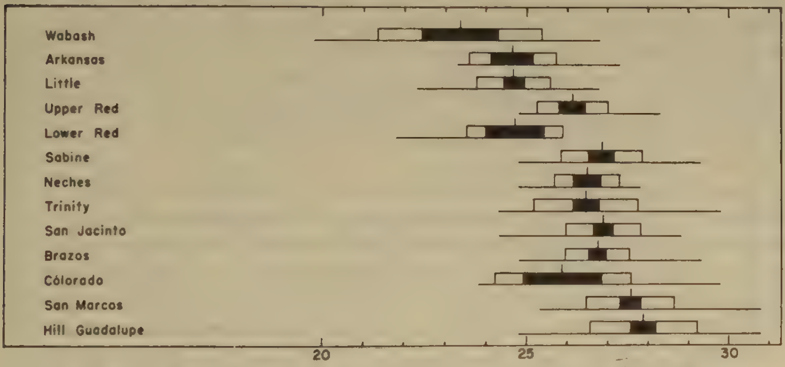

Fig. 5.—Pectoral length in hundredths of standard length + 0.07% per mm. of standard length

The caudal peduncle of the Wabash sample is the shortest on the average of any studied (fig. 4). This character provides a statistically valid distinc-

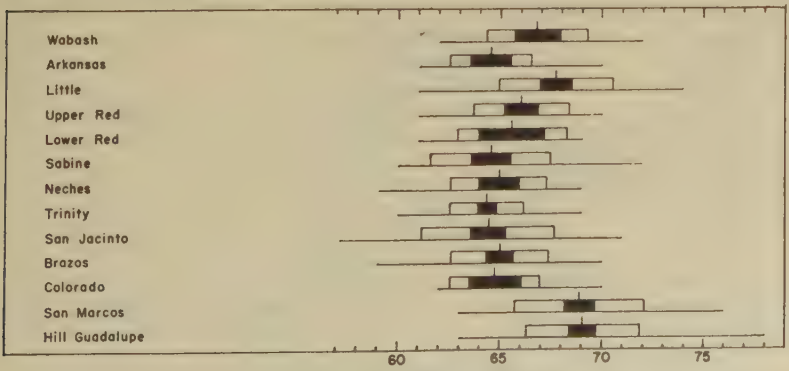

Fig. 6.—Lateral-line scales

tion in comparisons with all other samples except that from the Arkansas River. There is no overlap of the standard deviation bars of either the Wabash or Arkansas samples with those of the Little, Trinity, San Jacinto, Colorado, and Hill Guadalupe samples. The most extreme separation is with that of the Little sample.

Although the data just discussed suggest that morphologic types two and three are subspecifically distinct, I have not resurrected Jordan and Gilbert's name *serrula* for the southern type, because only one population of the northern type (*scierus* Swain) was studied. If analysis of other northern samples confirms the differences pointed out in this paper, the name *serrula* may be resurrected for a southwestern subspecies.

The characters used by Jordan and Gilbert (1886) to separate *serrula* from typical *scierus* prove inadequate for subspecific separation, as Hubbs and Black (1954) have noted. Jordan and Gilbert emphasized the smaller scales—68 to 71 in the lateral-line, as compared to 64 to 66 for Indiana specimens. My specimens from near the type locality of *serrula,* however, average 63.5 in scale count and near-topotypes of *scierus* average 65.6. Jordan and Gilbert's counts were either based on a small sample or on their San Marcos and New Braunfels specimens of *apristis,* which has smaller scales. The lighter color attributed to *serrula* refers to a character that varies with the clarity of the water and with season, sex, and preservation. The supposed difference in the squamation of the breast seems invalid, and this character varies with sex and season. The supposedly more distinct preopercular serrae apply only to the Brazos and Colorado samples, and the number of serrae in the Colorado basin sample overlaps the others too widely to be the chief subspecific character.

As is often true when more than one character distinguishes geographic races, the zone of intergradation between peripheral forms does not occur in the same region for all characters. The area of intermediacy in respect to the upper jaw length (fig. 7) and caudal peduncle length (fig. 4) is in the Arkansas River System. In snout length the line of intermediacy extends from Lake Texoma to Fort Smith, Arkansas. In pectoral length there is a somewhat similar broad area of intermediacy.

There are minor, probably racial, differences between the two samples of

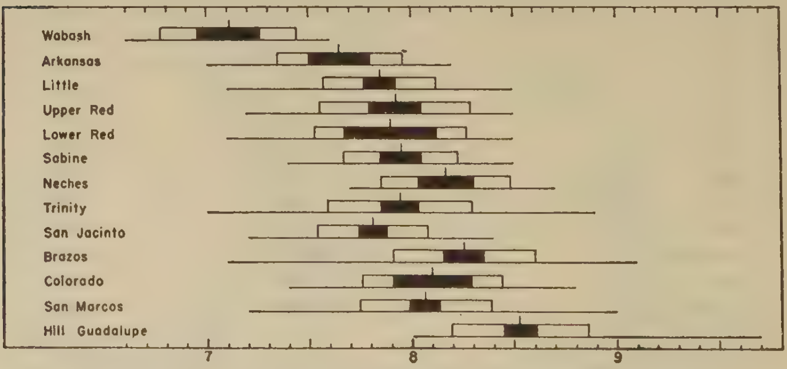

Fig. 7.—Upper jaw length in hundredths of standard length + 0.02% per mm. of standard length

morphologic type one (*apristis*) and among the several samples of type two.

The two samples of *apristis* show little or no statistically significant difference in five of seven characters presented, but exhibit statistically reliable differences in caudal peduncle depth (fig. 3) and in upper jaw length (fig. 7). The overlap, however, as measured by the standard deviation bars, is far too great to warrant subspecific separation. In the three characters shown in figs. 1, 5, and 6 the two samples of *apristis* agree closely and together contrast with all other samples.

In general, the samples of type two most closely approximated geographically (fig. 2) tend to be the most similar morphologically. The Colorado and Brazos samples are very similar, differing assuredly only in the number of preopercular serrae (fig. 1), in which respects both samples exceed any other.

The San Jacinto and Trinity samples closely resemble each other morphologically. The only reliable difference indicated is in the caudal peduncle depth (fig. 3), and the overlap in this respect is far too great for subspecific distinction. In only one character (fig. 3) are these two samples more similar to the Colorado and Brazos collections than to those from the Neches and Sabine.

The Neches and Sabine samples are especially similar, though there is an apparently trustworthy difference in the average length of the upper jaw (fig. 7). In most respects these samples closely resemble those from the adjacent Trinity and San Jacinto rivers to the southwest. Taken together, the Neches and Sabine samples resemble the Lower Red sample in all characters studied except the pectoral length (fig. 5), in which the Lower Red fish approach morphologic type three (typical *scierus*).

The Lower and Upper Red samples differ significantly, though not on the subspecies level, in three proportions (figs. 3, 5, 8). There are four more or less reliable differences between the Lower Red and Little samples (figs. 3, 4, 6, 8), but none of these distinctions would merit subspecies separation. The Lower Red fish are more similar to those of the Sabine and Neches than to the other samples of the same river system, namely those of the Upper Red and the Little. The Upper Red sample is not markedly similar to any other. It resembles the Trinity sample as closely as any other from Texas. The Upper

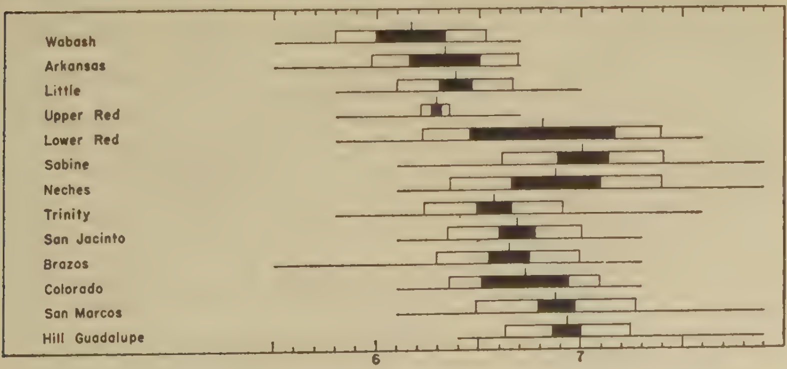

Fig. 8.—Snout length in hundredths of standard length

Red and Little samples differ in a number of respects. The snout length in the Upper Red sample is remarkably constant (fig. 8).

Each of the nine samples of morphologic type two can be separated on apparently reliable grounds from each other one by at least one character, and many pairs show little or no overlap between the standard deviation bars. It is possible that some other subspecific distinctions may be effected, but such action does not appear warranted from the present analysis.

SUMMARY

A darter endemic to the Guadalupe River System in Texas is described as a new subspecies of *Hadropterus scierus*. Its characters contrast with those of typical *H. scierus* and with those of the two other species of the same genus known to inhabit Texas waters, *H. shumardi?* and *H. maculatus*.

The two samples of *H. s. apristis* studied can be separated from each of 11 samples of *H. s. scierus* on apparently reliable grounds. Despite intersample variability, three morphological groupings occur: the two samples of *apristis*, nine samples from Texas and the Red River system in Oklahoma, and the Wabash River sample. The Arkansas River sample is intermediate between the latter two. Jordan and Gilbert's name *serrula* is not resurrected for the second morphologic grouping because the distinctions of the single northern sample may not hold when other samples are studied.

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DATA ON THE LIFE HISTORY, VARIATION, ECOLOGY, AND RELATIONSHIPS OF THE KELP PERCH, *BRACHYISTIUS FRENATUS*, AN EMBIOTOCID FISH OF THE CALIFORNIAS[1]

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This study was prompted by the publication of a revision of the Embiotocidae, a family of viviparous fishes of the North Pacific (Tarp, 1952). Some of the generic fusions adopted in that paper may well be accepted, others not. By far the least justified, in our opinion, was the synonymizing of *Brachyistius* with the very highly specialized genus *Micrometrus*. Since *Micrometrus*, along with the closely related genus *Amphigonopterus*, is charactized by outstanding peculiarities in life history, variation, and ecology, as well as in morphology (Hubbs, 1918, 1921), we undertook a preliminary study, in sufficient detail to determine whether *Brachyistius* agrees or disagrees with *Micrometrus* in these respects.

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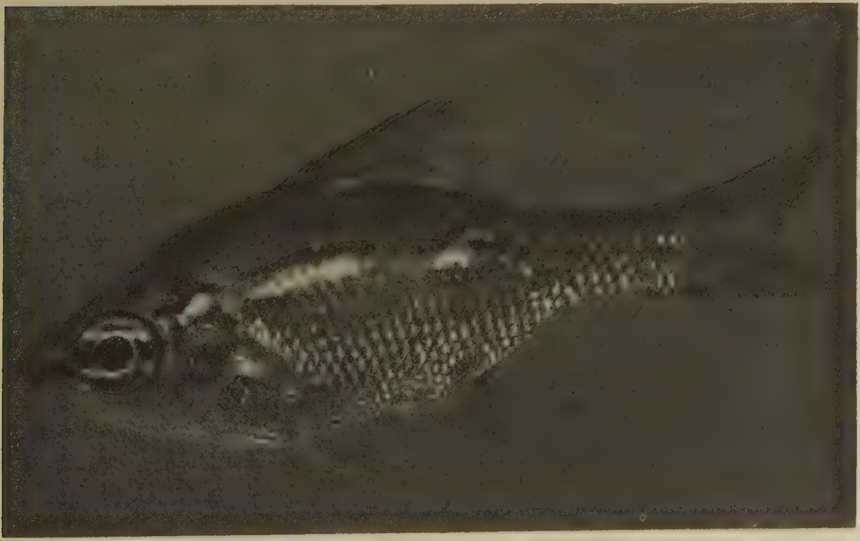

FIGURE 1. *Brachyistius frenatus:* photograph made by Scripps Institution of Oceanography, with stroboscope, of a live specimen from La Jolla, California, collected by Conrad Limbaugh, in the fall of 1951.

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The life-history and variational data on *Brachyistius frenatus*, the kelp perch (Figure 1), were taken on a collection of 350 specimens, including 13 term embryos, obtained with the aid of derris in the dense bed of giant kelp, *Macrocystis pyrifera*, off La Jolla Point, California, on August 1, 1950. The collection was undertaken by the ichthyology staffs of Scripps Institution of Oceanography and the University of California (Los Angeles), to sample as quantitatively as possible the fish life in the kelp bed, from surface to bottom. The sampling in the restricted area was extensive, but not wholly representative, although every effort was made to distribute the derris effectively and to secure all specimens possible, both from the surface, by dip-netting from skiffs, and underwater, by swimming with the aid of self-contained diving gear. Gulls made away with many surfacing specimens, including probably several hundred kelp perch, but they seemed to take the larger adults of this very small species as well as the young. It is thought that the sample of *Brachyistius frenatus* obtained is reasonably representative for the intitial and general life-history determinations that we now need. Undoubtedly the collection is by far the largest of the species ever made.

LIFE HISTORY

Life-history features of *Micrometrus* and *Amphigonopterus* for which we wished to determine the agreement or disagreement of *Brachyistius* are (1) the highly unique feature of the natal maturity of the males; (2) the slow growth rate and small size attained, a much less significant feature shared with the shiner perch, *Cymatogaster aggregata* Gibbons; (3) great sexual dimorphism in size, due to the slower growth and lesser viability of the males.

Age at First Maturity

Examination of the primary as well as the secondary sex organs of the 13 term embryos, including seven males, and of nearly all the 337 other specimens demonstrated that the males of *Brachyistius frenatus*, unlike those of *Micrometrus minimus*, the dwarf perch, and *Amphigonopterus aurora*, the reef perch (Hubbs, 1921), never mature before birth, or within several weeks thereafter. In this important biological respect, therefore, *Brachyistius* disagrees with the two micrometrins. In the natal maturity of the males, *Micrometrus* and *Amphigonopterus* are apparently unique among acanthopterygian fishes. The only other fish genera that we know to approach the micrometrins in this respect are the extremely neotenic pelagic *Schindleria*, and three cyprinodont genera, *Girardinichthys* and *Lermichthys* (Goodeidae) and *Cynolebias* (Cyprinodontidae). It has been held (Hubbs, 1921, p. 189) that another small embiotocid, *Cymatogaster aggregata*, matures before birth, but an examination of late embryos and of young born both in nature and in aquaria shows that the statement was incorrect. A life-history feature so unique as natal maturity surely is a strong indication of high specialization and of a long and independent line of evolution. The physiological adjustments involved must be profound.

As in *Cymatogaster*, which we think may be the most closely related genus, the males and females of *Brachyistius* seem to mature for the first time late in the first year of life. Of the young-of-the-year males taken on August 1, all of the smaller were definitely immature and some of the larger were maturing, in a proportion increasing with size. All of the older males, mostly and perhaps all yearlings, were mature. Of the females, all young-of-the-year were immature and the older ones, except for three still carrying embryos at this late date, were spent or apparently spent. The age at first parturition is one year. It remains to be determined just when copulation, sperm storage, fertilization, and embryogenesis take place. (Tables 1 and 2.)

Growth and Size

The data for the August 1 collection, consistent with other miscellaneous observations on this species and with general information on the life history of the viviparous perches, indicate, for southern California populations, that *Brachyistius frenatus* is born, in small numbers per female, at a standard length of about 32 to 33 mm., usually in the spring, rarely as late as August; that by August 1 the standard length of each sex ranges to 77 mm., with most of the young about 50 to 75 mm. long; that the usual size of the next size group, largely and probably all yearlings, reaches about 85 to 105 mm. by August 1; and that a few females, likely two years old, reach the length of at least 114 mm. (Tables 1 and 2, Figure 2). It seems improbable that many individuals live to the age of two years.

The 13 embryos of the August 1 collection, all 32 or 33 mm. in standard length, were taken from three females, 5 from one 88 mm. long, and 3 and 5, respectively, from females 93 mm. long. The smallest free-living young measures 33 mm.; five others, 34 to 37 mm. Their darkened pigmentation suggests that they had been born at least several days, perhaps a week or two previously. It is probable that in this species as in other embiotocids, growth ceases for several days, perhaps for a week or two—long enough to induce the formation of the natal annulus on the scales.

The skewed curve of size frequency for the free-living young of the year, with only 10 (3 percent) less than 48 mm. long, the small proportion (11 percent) of yearling and older females still carrying young, all full term, and the breeding habits of the family in general, indicate that the chief season of parturition is spring. There is no reason to infer that either the new-born young or the oldest fish occupy any other habitat, for the very extensive local collecting in surface waters, on the bottom, and on and just off the rocky reefs, has yielded too few specimens to suggest that the young live elsewhere than in the kelp beds. Growth after the formation of the natal annulus is probably rather slow, modally about 30 mm. by August 1. If the young are born chiefly about June 1, this would indicate an average daily increase of only 0.5 mm.

The specimens from 34 to 77 mm. long are judged to comprise the 0 age-group (the 1950 year-class) because of their size distribution and because all 13 fish aged of the 46 that are 68-77 mm. long, including 9 of the 13 that are 73-77 mm. long, have scales with no winter mark

TABLE 1

Size Frequency Data by Sex and Maturity for Brachyistius frenatus Taken in the La Jolla Kelp Bed on August 1, 1950

Sex and maturity	Standard length to nearest 5 mm.																	
	30[a]	35[a]	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115
Males, immature	3	8	2	1	9	23	33	35	8	1	--	--	--	--	--	--	--	--
maturing	--	--	--	--	--	--	--	5	6	1	--	--	--	--	--	--	--	--
mature	--	--	--	--	--	--	--	--	--	--	--	3	5	3	3	1	--	--
Females, immature	3	5	1	1	12	33	50	38	19	11	--	--	--	--	--	--	--	--
with young	--	--	--	--	--	--	--	--	--	--	--	--	1	2	--	--	--	--
spent[b]	--	--	--	--	--	--	--	--	--	--	--	2	7	8	4	1	--	2
Total males[c]	3	8	2	1	9	23	33	40	14	2	--	3	5	3	3	1	--	--
Total females[c]	3	5	1	1	12	33	50	38	19	11	--	2	8	10	4	1	--	2
Grand total	6	13	3	2	21	56	83	78	33	13	--	5	13	13	7	2	--	2

[a] Including 6 embryos 32 mm. long and 7 embryos 33 mm. long.
[b] Including some probably spent.
[c] Graphed in Figure 2.

TABLE 2

Number and Size, According to Age and Sex, of Specimens of Brachyistius frenatus Taken in the La Jolla Kelp Bed on August 1, 1950

Age and size	Specimens	Size range, mm. (Standard length)	Mean size, mm.
Term embryos, males	7	32–33	32.6
females	6	32–33	32.5
total	13	32–33	32.5
Young-of-the-year, males	128	33–77	60.5
females	167	34–77	60.9
total	295	33–77	60.7
Older fish, males	15	84–104	92.7
females	27	85–114	95.2
total	42	84–114	94.3

(only the natal annulus). The few fish of the next size group examined have, as expected, one winter annulus in addition to the natal mark.

The data indicate that the average growth increment from the first to the second summer is about 33 mm., or approximately the same as either the growth *in utero* or the modal increment between birth and August 1. The increase through the first year of maturity is very small.

The largest specimen in the August 1 collection, 114 mm. in standard length, is about the maximum that we have collected in southern California. Conrad Limbaugh, however, has seen some larger females about the Coronado Islands in May and June. The 35 specimens measured by Tarp (1952, p. 88) ranged to 121.5 mm. in standard length, but the largest probably came from central California, where on the average a greater length may be attained.

Relative Size and Number of Sexes

In *Amphigonopterus aurora,* as previously indicated (Hubbs, 1921) and in *Micrometrus minimus,* as a study of many collections has shown, the females markedly outnumber the males, except before and soon after birth. For both species additional data have confirmed the conclusion published in 1921, that the males not only die off sooner than the females, but also grow more slowly, so that the adults average much smaller. The size difference is already striking in yearlings, during the first period of maturity of females but the second season of breeding by the males. In correlation with the fact that they do not mature at birth the yearling males of *Brachyistius frenatus* are approximately of the same size range as the females and average almost as large (Figure 2). The slightly higher average indicated for the females measured may be due to the inclusion of two older fish. The ratio of males to females appears to decrease with age, as it does in *Micrometrus* and *Amphigonopterus,* but a similar decrease appears to take place in *Cymatogaster* and in other genera.

It is evident that in fundamental life-history features *Brachyistius* diverges notably from *Micrometrus* and *Amphigonopterus* and shows no agreement with these genera that is not shared also with *Cymatogaster.*

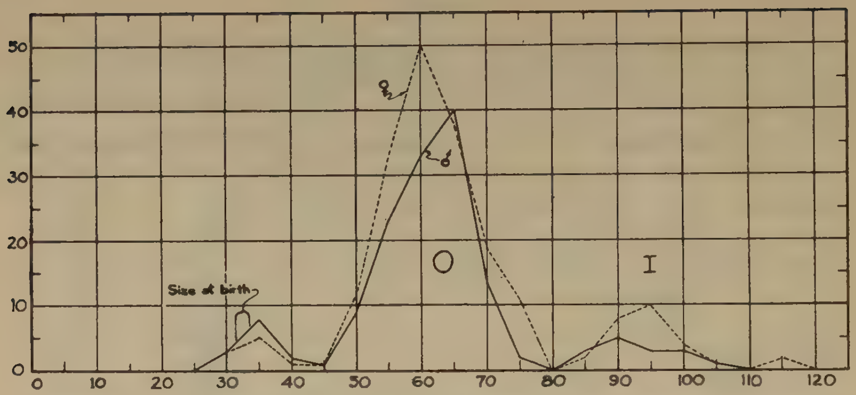

FIGURE 2. Size frequency distribution by sexes of 350 specimens of *Brachyistius frenatus* collected August 1, 1950.

SEXUAL VARIATION

We find that *Brachyistius frenatus* agrees with all embiotocids other than *Micrometrus minimus* and *Amphigonopterus aurora* and with nearly all other fishes in the essential identity of the sexes in the number of dorsal and anal rays (Table 3, Figure 3). The vertebrae have not been counted, but there is no reason to expect sexual dimorphism in their number. New counts of hundreds of specimens of *Micrometrus* and of *Amphigonopterus* confirm the previous findings (Hubbs, 1918) that in both these genera the males have more anal rays than the female, with relatively little overlap, and that on the average the males have more dorsal soft-rays and fewer dorsal spines, more caudal vertebrae, fewer precaudal vertebrae, and slightly more total vertebrae. The only other fishes in which there has been found more than a very slight average difference in the number of anal fin rays are the several species of *Cynolebias*, of the family Cyprinodontidae (Regan, 1913,

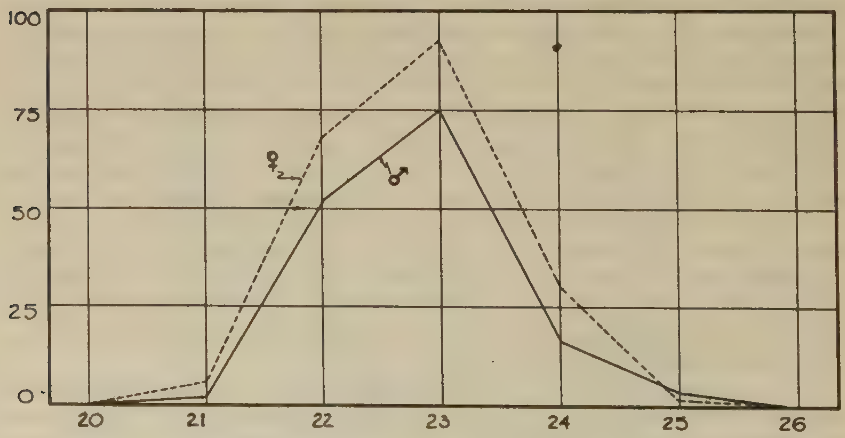

FIGURE 3. Frequency distribution of numbers of anal soft-rays in 350 specimens of *Brachyistius frenatus* collected August 1, 1950.

TABLE 3

Lack of Sexual Differences in the Number of Dorsal and Anal Fin Rays in Brachyistius frenatus
Based on the 150 males and 200 females collected August 1, 1950

Dorsal spines	7	8	9	10	No.	Mean	S. E.
Males	1	77	71	1	150	8.48	0.04
Females	--	96	103	1	200	8.525	0.04
Total	1	173	174	2	350	8.51	0.03

Dorsal soft-rays	13	14	15	16	No.	Mean	S. E.
Males	12	98	40	--	150	14.19	0.05
Females	19	118	59	4	200	14.24	0.05
Total	31	216	99	4	350	14.22	0.03

Anal soft-rays	21	22	23	24	25	No.	Mean	S. E.
Males [a]	2	52	75	17	4	150	22.79	0.06
Females [a]	6	68	93	31	2	200	22.775	0.06
Total	8	120	168	48	6	350	22.78	0.04

[a] Graphed in Figure 3.

p. 641-642; Myers, 1952) and the single species each of *Girardinichthys* and *Lermichthys*, of the Goodeidae (Hubbs and Turner, 1939). In these three genera, as Regan showed for *Cynolebias* and as Hubbs and Turner and also Robert Rush Miller have shown in unpublished studies for the two goodeids, the anal rays are, with very limited overlap, more numerous in males than in females. Some of the other smaller goodeids have on the average more anal rays in the male.

In the marked sexual variation in the number of anal rays, as well as in the natal maturity of the males, *Micrometrus* and *Amphigonopterus* are so far as known unique among all acanthopterygian fishes. These two highly distinctive features appear to be related. Embryological studies of *Micrometrus* and *Amphigonopterus* (made with the assistance of Elizabeth M. Kampa) show that fin-ray formation is not completed before the sexual dimorphism in body form has become established. In correlation with the need in these small viviparous fish for extra room in the female, to provide for adequate broods of the very large embryos, the abdomen in the female becomes longer and the urosome compensatingly shorter. Since the males and females are of the same size at birth, the shorter urosome of the female provides less space for fin rays than does the longer urosome of the male. Various studies have indicated that meristic parts are laid down at approximately constant absolute sizes, so that the number of parts is roughly proportional to the available space (Hubbs, 1941). An explanation is thus provided for the higher number of anal rays in the males of

Micrometrus and *Amphigonopterus* and for the other sexual differences in meristic counts in these genera. On the same basis it appears possible to explain the high number of anal rays in the males of *Cynolebias, Girardinichthys*, and *Lermichthys,* which also mature at or very soon after birth.

Since the sexes of *Brachyistius* do not differ in fin-ray number, this genus differs very strikingly from the micrometrins. The difference is almost surely very fundamental and of long standing, though it is accorded bare mention by Tarp (1952, p. 19, 87).

In counting the number of rays in *Brachyistius* we have followed the criteria recommended by Hubbs and Lagler (1947, p. 8-10). The usual condition in Embiotocidae, normal for most fishes, is a more or less close fore-and-aft apposition of the two elements of the last ray, but with the separation complete, in the concealed base as well as in the main exposed part of the fin. Tarp (1952, p. 23) wrote that ''the last ray of the dorsal and anal fin was counted as 1½ if it was split to the base,'' but he listed no ½ count for any species, though the normal situation is for the last ray to be completely divided through its extreme base. The ½ count is awkward and totally unnecessary. It would appear that Tarp, despite his stated criterion, usually enumerated the rays in Embiotocidae as virtually all ichthyologists have, for fishes, including embioticids, that typically have the two elements of the last ray closely approximated. Tarp added, however, that if the last ray ''was close to, but not visibly joined on the surface to the penultimate ray, it was counted as distinct.'' It is not clear whether he so referred to the unusual variants having the two elements of the last ray variably more separated than usual, or to the usual condition, in which the complete separation of the closely approximated elements of the last ray was disregarded. Tarp's range of counts for *Brachyistius frenatus* agrees with ours, except that he listed no variants with 10 dorsal spines and none with 25 anal soft-rays (which is not unexpected, since he had fewer specimens).

Occasionally in *Brachyistius* as in other spiny-rayed fishes one encounters, particularly at the junction of the spinous and soft parts of the dorsal fin, a ray that is intermediate between a spine and a soft-ray. If in postembryonic stages such a ray has any articulations it is listed as a soft-ray, no matter how spine-like the basal part may be. One of the 350 specimens has such a ray, definitely like a spine except for the articulated tip. Two others have the last spine as slender as a soft-ray, but since it shows none of the technical features of a soft-ray, it is enumerated as a spine. The smallest free-living specimen (33 mm.) retains one suture on the last dorsal spine. In the embryo this ray, like the third anal ray, begins as an articulated soft-ray, but gradually becomes transformed into a typical spine. Such transformation of the third anal ray was first determined for the mullets (Mugilidae) but is characteristic also of other families, as the Gerridae and the Embiotocidae. These rays, of course, are tallied as spines.

TABLE 4

Seasonal Variation in Number of Dorsal and Anal Rays in Brachyistius frenatus

Based on 308 fish-of-the-year collected August 1, 1950. The values are the means and, in parentheses, the standard errors, plus or minus.

Size-class		Number	Dorsal spines	Dorsal soft-rays	Anal soft-rays	These rays combined
mm.	Median					
32–52	42	45	8.40 (.07)	14.22 (.08)	22.69 (.10)	48.29 (.15)
53–57	55	56	8.43 (.07)	14.29 (.09)	22.75 (.09)	48.46 (.14)
58–62	60	83	8.51 (.05)	14.16 (.07)	22.82 (.09)	48.48 (.13)
63–67	65	78	8.54 (.06)	14.17 (.07)	22.71 (.08)	48.41 (.13)
68–77	72.5	46	8.65 (.08)	14.43 (.09)	23.22 (.12)	49.30 (.16)

SEASONAL VARIATION

Other variational analyses, made feasible by the large series of counts in a single collection, are here presented, though they do not bear on the main theme of the distinctiveness of *Brachyistius*. The first analysis (Table 4) pertains to seasonal variation. It has commonly been observed that the average number of parts developed, as of vertebrae and fin rays, decreases for spring-spawning fishes as the season advances and as the temperature during critical stages of development increases. In the present analysis, as is usual, the time of development is inferred from the size of the fish: the larger the fish, the earlier the development. The analysis is restricted to the 308 young of the year, for it is not safe to infer time of early development for yearling or older fish. The sexes are combined, since the data indicate no significant sexual dimorphism in the counts. The five-millimeter size-groups (Table 1) were combined as evenly as possible into classes with 45 to 83 specimens.

For dorsal spines, for dorsal soft-rays, for anal soft-rays, and for all these rays combined, the smallest size-class has fewer rays on the average than the largest class and the intermediate size-classes combined as a unit have intermediate averages for each comparison and intermediate averages for 10 of the 12 cases. The differences between the means for the smallest and the largest classes are of highly probable, though not entirely certain, significance: the differences between the means exceeds the standard error of the difference (the square root of the sum of the squares of the two standard errors) about 2.5 times for the dorsal spines, nearly 2 times for the dorsal soft-rays, more than 3 times for the anal soft-rays, and nearly 5 times (highly trustworthy) for all these rays combined. As is usual, the larger fish in the late-summer sample, that is, those that probably developed in the cooler water, have the higher average number of rays.

FIN-RAY CORRELATIONS

The fin-ray counts of the 350 specimens of *Brachyistius* taken on August 1, 1950, in the La Jolla kelp bed were tabulated in two ways (Tables 5-6) to see if this species agrees with the general rules, (1) that the elements in the anterior and posterior divisions of a single series are negatively correlated, and (2) that the elements in dorsoventrally or bilaterally opposed series are positively correlated. When the test is

TABLE 5

Fin-Ray Correlations in Brachyistius frenatus, Based on 350 Specimens Collected August 1, 1950

Dorsal spines	Dorsal soft-rays			
	13	14	15	16
7	--	--	1	--
8	2	87	81	3
9	29	127	17	1
10	--	2	--	--

r = —0.47 ± 0.04

Dorsal soft-rays	Anal soft-rays				
	21	22	23	24	25
13	3	15	11	2	--
14	5	80	101	28	2
15	--	25	55	15	4
16	--	--	1	3	--

r = +0.24 ± 0.05

Total dorsal rays	Total anal rays				
	24	25	26	27	28
21	--	2	--	--	--
22	6	61	46	5	--
23	2	54	112	35	4
24	--	3	10	7	2
25	--	--	--	1	--

r = +0.38 ± 0.05

TABLE 6

Association of Low and High Counts in One Fin With Low and High Counts in Other Fin

(Data from Table 5)

Based on 350 specimens collected August 1, 1950

Dorsal spines	D soft-rays	
	13-14	15-16
7-8	89	85
9-10	158	18

Chi-square=63
P=<0.01

Dorsal soft-rays	A soft-rays	
	21-22	23-25
13-14	103	144
15-16	25	78

Chi-square=9.5
P=<0.01

Dorsal rays	A rays	
	24-25	26-28
21-22	69	51
23-25	59	171

Chi-square=34
P=<0.01

made on the basis of the coefficient of correlation (r), indications are obtained of a moderate negative correlation (—0.47) between dorsal spines and dorsal soft-rays, a rather lower positive correlation (+0.38) between total dorsal and total anal rays, and a relatively low positive correlation (+0.24) between dorsal soft-rays and anal soft-rays. Coefficients of correlation of such magnitudes are commonly discredited, but added reliance is afforded by their agreement with the general rule.

Another statistical approach is to test by the chi-square method the association of low and of high counts in one fin with the low and the high counts in the other fin (Table 6). Highly trustworthy associations are indicated.

VARIATION IN RAYS IN OTHER FINS

Deviations in the number of anal spines from the normal (III) are extremely rare among the Embiotocidae, although noted by Tarp (1952, p. 41) for *Amphistichus argenteus* and by us for *Micrometrus minimus* and *Amphigonopterus aurora.* All specimens of *Brachyistius frenatus* counted (the 350 in one collection plus more than 20 in other series) have three anal spines.

Nor was any variation noted in the caudal count. In the 346 specimens with uninjured caudal fins in the large collection and in 8 specimens from other collections the count of principal rays is $7 + 7 = 14$. This appears to be the normal caudal ray formula for the Embiotocidae in general. Increasingly, distinctive caudal ray counts are being indicated as often of family or even higher than family significance, though of only generic and specific value in other groups, as Cyprinodontes and Heterosomata. Tarp (1952, p. 23) stated that he counted the principal caudal rays (that is, the branched rays plus 2), but he failed to record any counts or to mention the normal number.

The pelvic ray formula was I, 5 (normal for all Embiotocidae and for most spiny-rayed fishes) in 349 of the 350 specimens of *Brachyistius* comprising the large series and in 8 specimens from other places. The one variant had I, 4 rays in the left fin, which appeared fully normal and uninjured, and I, 5 in the right fin. A few deviations from the normal were noted by us in our extensive study of variation in *Micrometrus* and *Amphigonopterus,* emphasizing the principle that no meristic structure has an invariable number of parts.

ECOLOGY

The striking difference between *Brachyistius* and *Micrometrus* (as well as *Amphigonopterus*) in the usual habitat is another important biological distinction. *Brachyistius frenatus* is very intimately associated with the giant kelps, particularly with *Macrocystis,* whereas the two micrometrins are typically inhabitants of the exposed rocky reefs (Hubbs, 1921). *Amphigonopterus aurora* in its two regions (Central California and northwestern Baja California) appears to live exclusively in the intertidal belt, usually in rather open, shallow pools. *Micrometrus minimus* frequently occurs in rocky tide pools and is usually restricted to the inner margins of rocky reefs, though some live in coves between the rocky stretches and some inhabit the eel-grass (*Zostera*) of bays; a few wander out to a depth of a few fathoms, but stay near the bottom.

Brachyistius frenatus, in contrast, rarely approaches the intertidal belt of the reefs and very seldom occurs in tide pools. A few wander along the coast away from the giant kelp, but probably 95 percent or more of the total population lives in the kelp, at all ages. A few have been taken in traps set as deep as 90 feet. The normal habitat is at mid-depths among the rising columns of the kelp. The fish is well adapted to this habitat. Its color, typically more constant than indicated by Tarp (1952, p. 89), usually matches that of the kelp very closely, and seldom deviates far therefrom (individuals from deep water, however, may be deep orange). In the rather strongly oblique, almost superior position of the mouth it is typical of mid-water feeders and contrasts with the browsing micrometrins. The high and rather sharp fins with thin spines and delicate soft-rays befit such a fish.

The conclusions regarding the habitat of *Brachyistius frenatus* stem from extensive collecting particularly in Southern California and Baja California; from hundreds of hours of critical underwater observation in the kelp and elsewhere in California and Baja California, particularly by Conrad Limbaugh; and from repeated observations of the fish caught by the kelp harvesters. The collection from the La Jolla kelp bed that yielded 350 specimens of this species, not counting the several hundred seen to be eaten by gulls, contained in addition relatively few specimens of other embiotocids, namely *Embiotoca* sp. (4), rainbow seaperch, *Hypsurus caryi* (1), rubberlip perch, *Rhacochilus toxotes* (observed only), and pile perch, *Damalichthys vacca* (3).

A second species of *Brachyistius* was described by Tarp (1952, p. 89-90) as *Micrometrus* (*Brachyistius*) *aletes*, from Guadalupe Island, where we do not find typical kelp beds. We have obtained testimony indicating the occurrence of kelp beds around Guadalupe about 25 years ago and it seems not improbable that *Brachyistius aletes* lived among kelp when the specimens were collected in 1897 and 1911. At present it lives in and about *Sargassum* and *Eisenia*, which here form dense growths several feet high. In the crystal-clear waters about the island, *Brachyistius* descends to depths as great as 150 feet (Conrad Limbaugh, personal communication).

We have found floating drift kelp (*Macrocystis*, *Pelagophycus*, and *Nereocystis*) about Guadalupe Island and suspect that *Brachyistius* reached the island long ago with drifting kelp. Tarp (1952, p. 19), on the contrary, stated that "when Guadalupe Island was isolated from the mainland in fairly recent geological times, individuals from the mainland ancestral stock were isolated with it," and, further, that "through the joint action of geographical isolation and selection *M. aletes* arose." These statements violate the convincing evidence, geological and biological, that Guadalupe is an oceanic island.

In retaining carnivorous habits *Brachyistius frenatus* differs further from *Micrometrus* and *Amphigonopterus*, which are unique, in the family, in being chiefly (*Micrometrus*) or almost exclusively (*Amphigonopterus*) herbivorous, beyond the earliest free-living stage (Hubbs, 1921; Conrad Limbaugh, personal communication). Mr. Limbaugh has observed *Brachyistius frenatus* nibbling food material off the kelp. He has also seen it feeding, as *Oxyjulis* often does, on the ectoparasites of other fishes, which submit willingly to this cooperative act. In general, *Brachyistius* and *Oxyjulis* have similar feeding habits, and, as noted below, similar dentition.

RELATIONSHIPS AND NOMENCLATURE

We thus find that *Brachyistius frenatus* diverges widely from *Micrometrus minimus* and *Amphigonopterus aurora* in various fundamental features of life-history, variation, habitat, and food, in which respects *Micrometrus* and *Amphigonopterus* are unique in the family (in two respects, natal maturity of the males and a strong sexual dimorphism in the number of anal rays, unique among all spiny-rayed fishes). Such considerations are of greater significance in judging relationships than even rather profound differences in morphology, certainly vastly more indicative of genetic ties than the few superficial similarities that led Tarp (1952) to synonymize *Brachyistius* with *Micrometrus,* recognizing it only as a subgenus.

It is difficult to ferret out the reasons for the reference of *Brachyistius frenatus* to *Micrometrus.* Tarp presented an entirely artificial (though useful) key, with no attempt at natural groupings and his discussions of generic relationships are interwoven in a speculative and unfruitful attempt to retrace the phyletic history of the family in terms of both space and time. Particular stress seems to have been placed on the finding in *Brachyistius aletes* of a blackish axillary crescent approaching that of *Micrometrus minimus* and *Amphigonopterus aurora*—surely a very superficial feature. Stress was also laid on the short dorsal fin base and the correspondingly long interval between the dorsal and caudal fins, in which minor respects *B. frenatus* agrees somewhat better with *M. minimus* and *A. aurora* than with *Cymatogaster aggregata* and *C. gracilis.* But the proportional measurements given by Tarp indicate that species of other genera overlap those of *Micrometrus* (in the sense of Tarp) and those of *Cymatogaster.* The agreement between *Brachyistius* on the one hand and *Micrometrus* and *Amphigonopterus* on the other in the small size attained and in the large size of the scales is no justification for generic fusion, for in these rather superficial respects all three genera agree essentially with *Cymatogaster,* which genus we regard as probably the nearest living relative of *Brachyistius.*

There are very adequate morphological grounds for the generic separation, at least, of *Brachyistius* from the Micrometrini (*Micrometrus* and *Amphigonopterus*). The differences in structure far transcend the few items of agreement. The teeth of the jaws are conic instead of being very broad incisors, rendered tricuspid by the expansion of the shoulders. A few of the lateral teeth in the micrometrins may be nearly conic, but Tarp (1952, p. 82) underestimated the distinctiveness of the dentition of the micrometrins, unique in the family, by stating, ''teeth very often tricuspid, but the constancy of this character is not marked.'' There are other striking differences in dentition. The teeth form a somewhat irregular series of points rather than an even crenate cutting edge. The teeth are weak to obsolete on the side of the jaws, instead of extending evenly around onto the sides. Much as in such labrids as *Oxyjulis californica* there are two to four canines at the front of the lower jaw and four closely approximated canines at the front of the upper jaw, whereas in the micrometrins there is no specialization of the teeth at the front of the jaws. The mouth of *Brachyistius* is strongly oblique, largely on a level with the eye, and somewhat superior (with the lower jaw projecting), rather than being subhorizontal, largely or wholly below the level of the eye, and slightly inferior (with the lower jaw weakly included)—in all, fitted for grazing plants off the rocks rather than for snapping up small animals in mid-water. In correlation with the mouth structure the muzzle in *Brachyistius* is much more prominent than in the micrometrins and the top of the head is convex instead of concave.

The whole structure of the integument and fins in *Brachyistius* is more delicate than in the micrometrins. The spines and soft-rays are much thinner. The lower pectoral rays are scarcely instead of notably free and silky. The dorsal spines are graduated almost to the end rather than forming a rounded or flat-topped fin. The anal fin is sharply elevated at the front instead of being flat or rounded. In the adult males this sharp anterior elevation of the fin becomes exaggerated, greatly so in high males, and other sexually dimorphic differences appear, further emphasizing the increasingly evident principle that such sex-limited characters in fishes as well as in insects and other groups are of prime taxonomic significance. The spines become shortened and the first soft-ray considerably thickened. The sixth to eighth rays, lying under the main part of the thickened glands, become weakened, sometimes extremely weak, while the ninth to eleventh rays, under the end of the glands and just behind them, become very much strengthened and widened (except near base and tip), so that the articulations become linear horizontally. The interradial membranes here are thickened and opaque. The several following rays are more or less modified in the same direction. In high males the thickened rays are so widened as to be in contact, forming together a rather solid plate. In the Micrometrini the spines do not become much shortened in the adult males and the first soft-ray is not particularly thickened. The soft-rays under the middle part of the glandular area (about the fifth to eighth)—the very ones that are weakened in *Brachyistius*—are moderately strengthened and widened. And the rays over the end of the glands and just behind—the ones that become so greatly thickened in *Brachyistius*—are definitely weaker than those to either side. Nowhere do the rays broaden into mutual contact.

A more sharply marked difference is the lack in *Brachyistius* of the deeply concave, fine-scaled oval depression on the body above the front of the anal fin (a structure that seems designed to receive the anal spines of the female during amplexus). This structure was used (Hubbs, 1918) as a criterion of subfamily Micrometrinae (comprising *Micrometrus* and *Amphigonopterus*), but, as Tarp has shown, a similar though smaller and less highly differentiated structure (very possibly, we think, of independent origin) characterizes certain other genera (*Cymatogaster*, *Ditrema*, *Neoditrema*, and *Hysterocarpus*). In his phyletic discussion (p. 17-21) Tarp laid stress on the development of this structure, which he renamed the "lunar-shaped depression," and he included *Brachyistius* in the evolutionary line developing this feature, stating (p. 87): "occasionally a very slight depression found in the body surface of the male, dorsal to the anterior portion of the anal fin, adumbrates the conspicuous concavity which characterizes the subgenus *Micrometrus*." But we fail to find the structure (which involves much more than a mere concavity) in *Brachyistius*.

Tarp's valuable discovery of additional features separating the Amphistichinae from all other embiotocids—a separation that we still further confirm—renders it logical to follow Tarp in dividing the family first into the Amphistichinae and the Embiotocinae. The subfamily Micrometrinae (Hubbs, 1918) should, we feel, be subordinated to tribal rank, as the Micrometrini. We accord the same rank to the very distinctive freshwater genus *Hysterocarpus*, recognizing for it the tribe Hysterocarpini. Prior to 1918, when it was classed in the Embiotocinae by Hubbs (and when tribal rankings were not recognized in ichthyology), *Hysterocarpus* was regarded as the type of a distinct subfamily. Both groups seem to us to call for more than generic separation and their distinction as tribes within the Embiotocinae contrasts them satisfactorily with all the other genera, which may constitute the tribe Embiotocini.

Within the Micrometrini we recognize two monotypic genera, *Micrometrus* and *Amphigonopterus*. The characters heretofore used to separate *Amphigonopterus* (Hubbs, 1918) seem on the basis of current trends of thought hardly adequate to justify generic separation, but on further examination we now discover much more trenchant characters, involving fundamental differences in the genitalia of the female and in the complex architecture of the oval depression in each sex, justifying, in our opinion, the recognition of both genera. These differences are outlined in a manuscript, in preparation, dealing with the taxonomy of the whole family.

SUMMARY

A study of the viviparous embiotocid fish *Brachyistius frenatus* of western North America, based chiefly on a collection of 350 specimens, shows that this species differs greatly and fundamentally from *Micrometrus minimus* and *Amphigonopterus aurora* in various features of life history, variation, and ecology, as well as in morphology. The males do not mature earlier than late in the first year of life, rather than before birth (in the natal maturity of the males *Micrometrus minimus* and *Amphigonopterus aurora* are unique among all spiny-rayed fishes). Growth is slow: the standard length at birth, which appears to take place chiefly in the spring, rarely as late as August 1, is 32 or 33 mm.; by August 1 the average length has nearly doubled, to about 60 mm.; by the next August 1 the length at birth has hardly trebled (to about 90 or 95 mm.). The sexes of *Brachyistius*, unlike those of *Micrometrus* and *Amphigonopterus*, grow at about the same rate during the second as well as the first year of life. At one year of age, females first give birth to young. A few females may live to be two years old. The ratio of males to females appears to decrease with age.

In having the number of rays in the dorsal and anal fins the same in the two sexes *Brachyistius* further differs fundamentally from *Micrometrus* and *Amphigonopterus*, in which the marked sexual dimorphism in number of rays, particularly in the anal fin (unique among spiny-rayed fishes), is attributable to the attainment of adult proportions before birth (the greater length of the abdomen in the late

female embryos, attained before the formation of rays is complete, leaves less room for anal rays to form in that sex).

In *Brachyistius frenatus* the average number of rays formed appears to decrease as the season advances and as the developing fish are subjected to increasingly higher temperatures, since in the August 1 collection the largest (first-born) fish of the year have on the average more rays than the smallest, last-born fish. In agreement with the general rules that the number of elements in the anterior and posterior parts of a single series are negatively correlated and that the number of elements in opposed parts are positively correlated, we find a negative correlation between the numbers of dorsal spines and of dorsal soft-rays and a positive correlation between the numbers of dorsal and anal rays. The number of anal spines in the 350 specimens is invariably 3, the principal caudal rays number 7 + 7 in all 346 counted. One specimen among 350 had 4 pelvic soft-rays on one side.

In being carnivorous *Brachyistius* differs further from the almost strictly herbivorous *Micrometrus* and *Amphigonopterus*. Unlike those reef-inhabiting genera, *Brachyistius* is almost confined to the beds of giant kelp, particularly *Macrocystis*, where it lives chiefly in midwater. Its characters are adaptive to its habitat and way of life. Its dentition is quite different from that of *Micrometrus* and *Amphigonopterus* and there are other notable morphological differences, particularly in the sexual modifications of the anal fin and in the lack of the oval depression near the anal fin, which is elaborately and distinctively developed in *Micrometrus* and *Amphigonopterus*. *Brachyistius* appears to be more closely related to *Cymatogaster* than to *Micrometrus* and *Amphigonopterus*. On the basis of present evidence it seems best to divide the Embiotocidae first into two subfamilies, Amphistichinae and Embiotocinae, and to recognize three tribes in the Embiotocinae, namely Embiotocini, Micrometrini for *Micrometrus* and *Amphigonopterus*, and Hysterocarpini for the fresh-water genus *Hysterocarpus*.

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G. F. McEwen, M. W. Johnson and Th. R. Folsom:

A Statistical Analysis of the Performance of the Folsom Plankton Sample Splitter, Based upon Test Observations.

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(Scripps Institution of Oceanography, La Jolla, California.)

A Statistical Analysis of the Performance of the Folsom Plankton Sample Splitter, Based upon Test Observations[1].

By

G. F. McEwen, M. W. Johnson and Th. R. Folsom.

With 11 Figures.

Summary. The device for splitting a plankton sample into two approximately equal parts consists of a hollow cylindrical drum mounted to turn on a horizontal axis, and a vertical semi-circular septum cemented into place midway between the end walls of the drum. About a quart will fill the drum up to the axis. After rotating the drum until the septum is above, the sample is poured in. Then the drum is rotated until the septum splits the sample. Lifting the drum and rotating a little more, the two separated samples are drained into containers of convenient shape for emptying and filling. Smaller samples are obtained by emptying one container into the drum. Thus aliquot portions of approximately $^1/_2$, $^1/_4$, $^1/_8$, etc. of the original are obtained, and the process is continued until the sample is small enough for counting. In general the sample consists of a number of different kinds of plankters each of which is counted separately. Multiplying each count in the mth fraction by 2^m gives an estimate of the number in the original sample. Each step in the splitting process is subject to random errors and possibly biased errors. Studies of these errors are based upon a series of test runs involving both volume measurements and plankton counts.

The samples split were specially chosen to represent different types of plankton communities. The several types tested proved not to influence the results materially.

Statistical tests involving distribution of χ^2 and departure from the mean, of left and right portions gave convincing evidence that the errors were random. Thus, averaging separate counts would be expected to reduce the error. Researches on the magnitude of the error were based upon the law of propagation of errors of a product. Furthermore a study of the difference between the left and right samples as well as other investigations on the different sources of error have been made.

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[1] Contribution from Scripps Institution of Oceanography, new series No. 689.

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The paper concludes with a detailed description of the device and a discussion of various aspects of the plankton problem, such as variability of distribution in the sea, tendency to occur in swarms, laboratory techniques, recognition of the different kinds of plankters and the practical value of instruments and statistical tests from the point of view of the biologist engaged in quantitative researches on marine plankton.

Zusammenfassung. Die Apparatur zur Teilung einer Planktonprobe in zwei ungefähr gleiche Hälften besteht aus einer hohlen Zylindertrommel, die auf einer horizontalen Achse drehbar montiert ist, und einer vertikalen halbkreisförmigen Scheidewand, die mitten zwischen den beiden Grundflächen der Trommel eingebaut ist. Die Trommel wird durch etwas mehr als einen Liter ungefähr bis zur Achse gefüllt. Man dreht die Trommel, bis die Scheidewand oben ist, und füllt dann die Probe ein; dann wird die Trommel gedreht, bis die Zwischenwand die Probe teilt. Durch Heben und leichtes Weiterdrehen der Trommel werden die beiden getrennten Proben in geeignete Behälter abgefüllt. Kleinere Proben erhält man durch Entleerung eines Behälters in die Trommel, so daß Teilmengen von $^1/_2$, $^1/_4$, $^1/_8$ usw. der ursprünglichen Menge erhalten werden, bis die Probe klein genug für eine Auszählung geworden ist. Im allgemeinen besteht die Probe aus einer Anzahl verschiedener Planktonarten, die einzeln ausgezählt werden. Durch Multiplikation jeder Auszählung der m-ten Fraktion mit 2^m ergibt sich eine Schätzung der Zahl in der ursprünglichen Probe. Jeder Schritt bei diesem Unterteilungsverfahren kann mit zufälligen, möglicherweise auch mit systematischen Fehlern behaftet sein. Eine Untersuchung dieser Fehler basiert auf einer Serie von Testversuchen über Volumenmessungen und Planktonzählungen.

Die Teilproben wurden speziell ausgewählt, um verschiedene Typen von Planktongesellschaften zu erfassen; ein systematischer Fehler der Auswahl ließ sich dabei nicht erkennen. Eine statistische Prüfung unter Benützung von χ^2 und mittlerer Abweichung zwischen Rechts- und Linksteilen ergab den Beweis, daß nur zufällige Fehler auftreten, deren Einfluß sich durch Mittelbildung vermindern läßt. Untersuchungen über die Größe der Fehler werden mit Hilfe des Fehlerfortpflanzungsgesetzes durchgeführt. Außerdem wurde eine Untersuchung über die Beziehungen zwischen Rechts- und Linksproben und über verschiedene Fehlerquellen durchgeführt.

Die Arbeit gibt zum Schluß eine genaue Beschreibung der Apparatur und eine Diskussion der verschiedenen Probleme der Planktonforschung, wie z. B. Veränderlichkeit der Verteilung im Meer, Tendenz zur Schwarmbildung, Laboratoriumstechnik, Erkennung verschiedener Arten von Plankton und praktische Bedeutung der Instrumente und der statistischen Methoden unter den Gesichtspunkten des Biologen, der quantitative Untersuchungen des Meeresplanktons durchzuführen hat.

Résumé. L'appareil destiné à diviser en deux parties à peu près égales un échantillon de plancton, consiste en un récipient ayant la forme d'un tambour cylindrique. Celui-ci est fixé de manière à tourner autour d'un axe horizontal; une paroi semi-circulaire verticale (septum) est fixée à l'intérieur du tambour et placée à mi-chemin entre les deux parois du fond de celui-ci. Un peu plus d'un litre suffira à remplir le tambour jusqu'à l'axe. Après avoir tourné le récipient jusqu'à ce que le septum se trouve en haut, on verse alors l'échantillon dans le tambour; on tourne ensuite celui-ci jusqu'à ce que le septum partage l'échantillon. En levant et en tournant encore

un peu, mais lentement, on verse les deux parties de l'échantillon dans des récipients appropriés. On peut continuer à partager l'échantillon, en versant le contenu d'un des récipients dans le tambour et ainsi de suite. On obtiendra de cette façon des portions égales à $^1/_2$, $^1/_4$, $^1/_8$ de la quantité primitive, jusqu'à ce que l'échantillon soit assez petit pour que son contenu puisse être compté. En général l'échantillon contient différents constituants du plancton qui sont comptés chacun séparément. En multipliant par 2^m le résultat de chaque compte de la m^{ienne} fraction, on obtient une estimation du nombre contenu dans l'échantillon original. Chacune de ces opérations de partage est sujette à des erreurs de hasard, parfois aussi à des erreurs systématiques. L'étude de ces erreurs est basée sur une série d'épreuves comprenant des mesures de volume et des calculs de plancton. Les différents échantillons partiels ont été choisis particulièrement pour représenter différents types d'associations de plancton. Plusieurs types, spécialement étudiés, ont prouvé que les résultats n'avaient pas été faussés. Des tests statistiques comprenant la distribution de χ^2 et l'éloignement des parts de gauche et de droite de la moyenne, prouvent que les erreurs sont dues au hasard. De cette façon on réduira le mieux l'erreur en prenant la moyenne des différents comptes. L'étude de la grandeur de l'erreur a été faite à partir de la loi de propagation des erreurs d'un produit. En outre, on a étudié la différence entre les échantillons de droite et de gauche ainsi que d'autres problèmes des sources d'erreur.

L'article se termine par une description détaillée de l'appareil et discute les différents problèmes relatifs au plancton, tels que la variété de sa distribution dans la mer, sa tendance de se grouper en essaims, en outre les techniques de laboratoire, la façon de reconnaître les différents constituants du plancton et la valeur pratique des instruments et des méthodes statistiques du point de vue du biologue s'occupant des recherches quantitatives sur le plancton marin.

Introduction.

The animal population of the oceans is divided into three major categories depending upon the habitat and, in the pelagic forms, on the degree of locomotory powers. Thus, we recognize 1. the *benthos*, or bottom-dwellers; 2. the *nekton*, or fast-swimming pelagic forms; and 3. the *plankton*, or drifting or weakly-swimming pelagic life. Of these three, the plankton is by far the most abundant, and consists of countless numbers of different species distributed in various concentrations from the surface to great depths.

In ecological investigations involving a consideration of the relative abundance of the various species of the plankton community, the biologist is confronted at the outset with two great difficulties, other than taxonomic: 1. the collection of representative, quantitative samples, and 2. the numerical evaluation of the very large number of small organisms within the samples.

The first difficulty is minimized by collecting numerous samples from different levels and by using large nets with mesh-size most suitable for capture of the organisms wanted. In recent years, flowmeters are commonly placed within the net to provide a measure of the amount of water filtered.

The second difficulty necessitates splitting of the sample into small aliquot parts in order to make it practicable to examine and count directly the various species dealt with. The results of these counts are multiplied by the proper factor to give the numbers present in the complete sample. It is an evaluation of this operation that we are mostly concerned with here.

The senior author is responsible for the statistical procedures, Dr. FOLSOM for the instrumentation and Dr. JOHNSON for the biological analyses.

It is a pleasure to acknowledge the assistance of DELPHA McGOWAN and MARGARET RIEDEL in the enumeration of the organisms and ROBERT BIERI and EDWARD BRINTON in the statistical calculations.

Apparatus.

The devices which have been perfected for fractioning of dry materials, such as sand or grain (OTTO, 1937) cannot be used with assurance when dealing with wet material or organisms such as plankton in fluid. The individual plankters are characterized by different degrees of buoyancy and shapes. Hence, unless they are continuously agitated by stirring, they finally settle out and come to rest more or less into strata. Special effort must be made to choose a splitting technique which is not influenced by this non-random vertical distribution. In 1948 a new device was developed by T. R. FOLSOM at Scripps Institution of Oceanography for routine splitting of plankton samples. This device, which will be described in greater detail elsewhere by FOLSOM has been in continuous use here for the past five years and has earned complete acceptance in its intended use. There is reason to believe that it may be equally useful for sampling other kinds of materials in fluid. Dr. FOLSOM prepared the following brief description of the device.

Fig. 1 is a working drawing of the model which has seen the longest routine service. The dimensions are given by means of a scale. It was constructed entirely of plastic materials and stainless steel and is not corroded by sea water.

The splitting device consists of a hollow cylindrical drum which is provided with an axle which terminates in two plastic handles. The handles act also as trunnions, and during the splitting operation are rested on a pair of saddle-bearings supported by legs. The drum can be rotated around this axis through at least 180 degrees.

An essential feature is the semi-circular septum which is carefully spaced and cemented into place midway between the end walls of the drum. One free edge of this septum is polished and more or less sharpened and acts as the splitting knife. The other free edge merges into and constitutes one part of the bifurcating spout as can be seen in the figure. A notch is cut out of the drum to permit filling and emptying.

Insert (*a*) of Fig. 1 and Fig. 2*a* illustrate the filling procedure.

Insert (*b*) of Fig. 1 and also Fig. 2*b* illustrate how rotation of the drum causes the splitting blade to pass through the sample.

Insert (*c*) of Fig. 1 and also Fig. 2*c* show how the two halves of the sample are poured out when rotation is continued while the trunnion handles are lifted slightly. Plastic boats of convenient shape for emptying and filling the drum are provided.

General Operational Procedure.

The aggregation of organisms caught in the field by the net are preserved in a weak solution of formalin, usually in one-quart jars. The splitting is done directly on these fluid samples after large jellyfish, etc. have been removed and the sample thoroughly mixed before pouring into the drum.

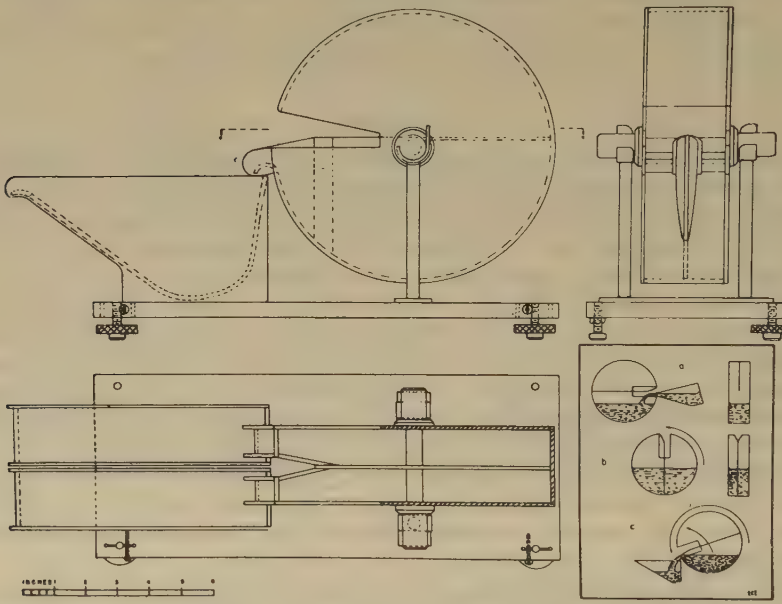

Fig. 1. Diagram of the zoo-plankton sample-splitter.

Leveling screws and a mechanics level are attached to the base plate of the device since the axle must be maintained level until the blade has passed completely through the sample. This is the only adjustment which must be made when the instrument is set up.

Smaller samples are made by returning the contents of one boat to the drum and splitting this once more. Each step takes only a few minutes, so the specimen can be quickly split into thirty-two or more parts.

The enumeration of organisms is accomplished by placing the smallest aliquot in a suitable counting chamber and identifying and counting directly with the aid of a low power microscope.

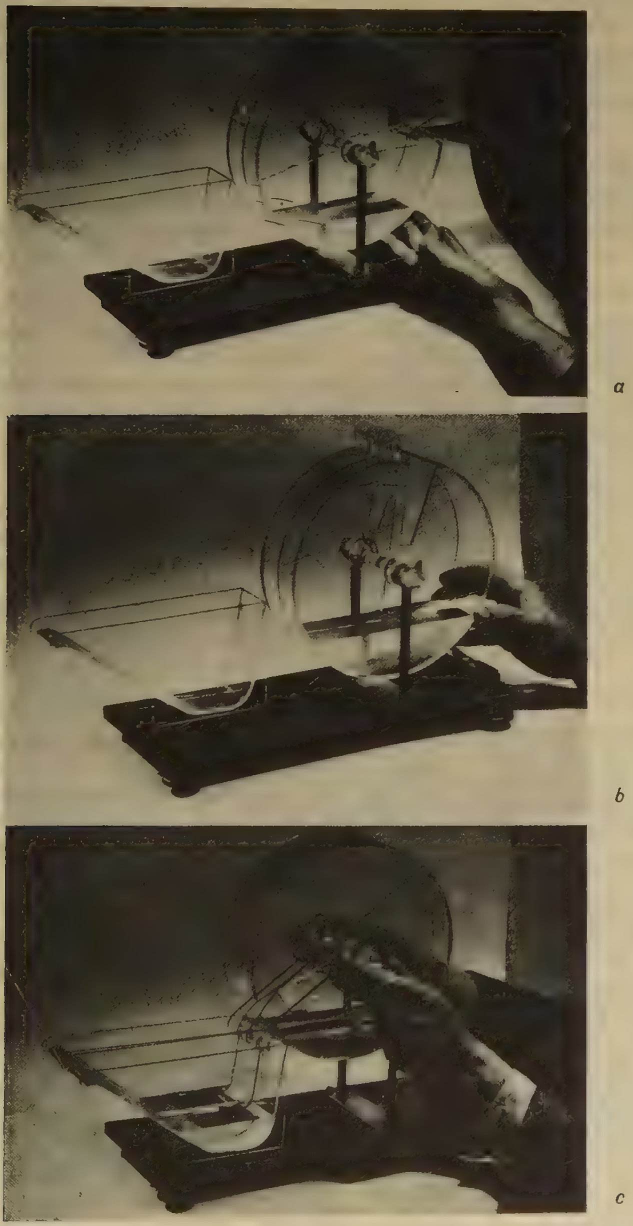

Fig. 2. *a* Pouring a zoo-plankton sample into the splitter. *b* View of the splitting blade sweeping through the sample. *c* View of the two halves of the sample just poured out of the drum.

In measuring the total volumes of organisms in the complete sample, or in each fraction of it, the sample including organisms and fluid is measured, then the fluid alone is measured after the organisms have been removed with an appropriate strainer. The difference gives the "displacement" or "wet" volume of the organisms.

Statistical Analysis of the Performance of the Plankton Splitter.

About three years ago, E. H. Ahlstrom reported preliminary studies of the Folsom plastic fractioner based upon plankton volumes and counts of twenty paired samples of fish eggs and larvae split into two portions. He added the total χ^2 values for each, computed from the special formula $\frac{(L-R)^2}{L+R}$, and concluded that these totals were no larger than could reasonably arise from random errors. Plankton volumes were fractioned to obtain 50%, 25%, and $12^1/_2$%, portions and sums of these portions were found to agree well with previous amounts. He found that the small errors tended to average out. These encouraging results suggested the present undertaking to conduct a detailed analysis of the performance of the device.

In quantitative plankton work, the size of the net hauls is often so large as to preclude counting of the individuals. Accordingly, various expedients are used to get some idea of relative numbers. For example, the haul may be poured into a graduate, and, after settling for a definite time interval, a measure of the volume of the settled material may be used. But, in the absence of exact counts of the net haul, a representative small sample containing correct proportions of each kind of plankton would meet the requirements. Then the number of each, in such a sample, can be directly counted, and the result multiplied by the denominator of the fraction $\frac{1}{2^m}$, where $m = 1$, for the first sample; 2, for the second, etc., is a quantitative estimate of the number in the original sample.

However, no matter how well the sampling device may be designed and built, even when used with the greatest care, errors in the results are unavoidable. Thus, quantitative researches on plankton require an answer to two questions: Are the errors random? How large are the errors?

For this purpose special test series of observations were made, including volumes of the fractioned samples and counts of the plankton. Fig. 3 shows the general plan of this operation. From the original sample designated by 0, two values 1 and 2 were obtained, then 1 was split into two halves, 3 and 4; and 2 was split into the halves 5 and 6, and so on. The samples indicated by circle 0 were kept but not split. Proceeding in this way to the mth fraction, there would be m pairs of samples, and the odd numbers in the diagram would be left-hand samples and the even numbers would be right-hand samples, denoted by L and R in this paper. In the test series both the L and R samples were counted, and each was designated by a number indicating its place in the plan of operation.

The first test for randomness was based upon $2\,S_i^2 = \frac{(L_i - R_i)^2}{2}$ equals the unbiased value of the variance of L_i or R_i. From one, two, or three groups of hauls grouped according to size unbiased averages of the variance $\sigma^2 = \frac{\sum_{1}^{k} 2\,S_i^2}{k}$ were computed. Then the ratio $\frac{2\,S_i^2}{\sigma^2}$ is a nondimensional quantity that has a known χ^2 distribution of one degree of freedom if the errors are random. The theoretical χ^2 curve is the same in Figs. 4*a–c* and 10. After arranging the values $\frac{2\,S_i^2}{\sigma^2}$ for each kind of plankton in their order of magnitude, the proportion of entries equal to or exceeding each observed value is found, thus determining the position of the points ⊙ on the diagrams.

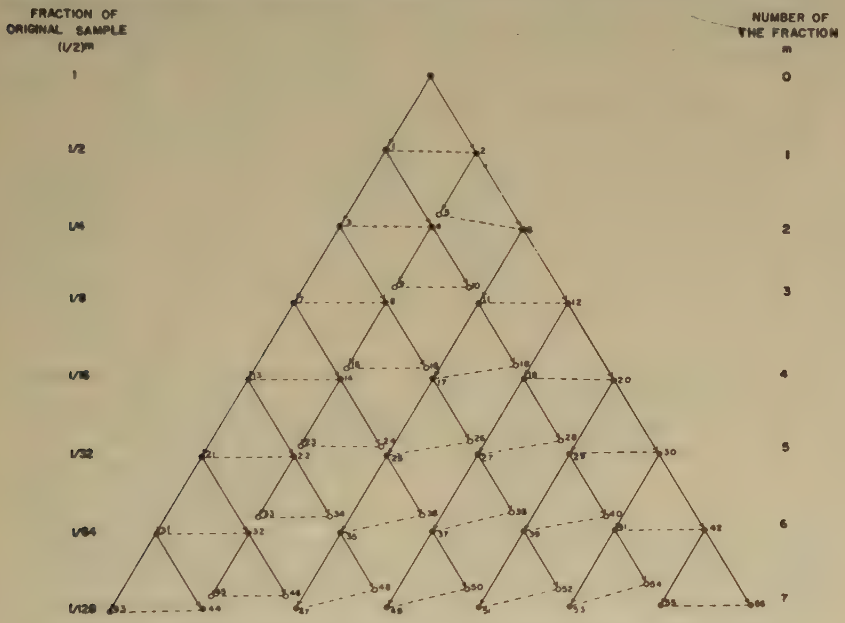
FRACTION OF ORIGINAL SAMPLE $(1/2)^m$
1
1/2
1/4
1/8
1/16
1/32
1/64
1/128
NUMBER OF THE FRACTION m
0
1
2
3
4
5
6
7
2
10
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Fig. 3. Diagram for making test observations with the Folsom sample-splitter.

The general agreement of these points with the theoretical curve, Figs. 4*a* and *b*, is convincing evidence of randomness. The same observations for amphipods and euphausiids and for a composite of six kinds of plankton, Fig. 4*c*, have been subjected to an additional test of randomness by plotting the observed distribution of (departure of the mean) = x, expressed in units of σ, equals $\frac{x}{\sigma}$, against the theoretical normal or Gaussian cumulative distribution curve, Figs. 5*a–c* and 11

$$\frac{1}{\sqrt{2\pi}} \int_{x/\sigma}^{\infty} e^{-\frac{t^2}{2}}\, dt.$$

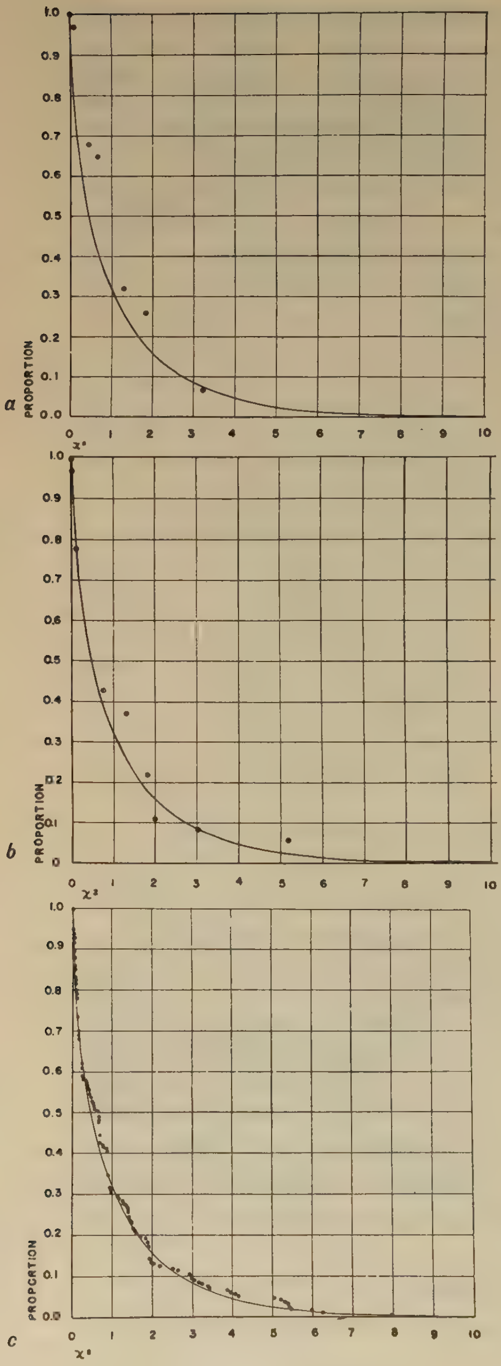

Fig. 4. χ^2 distribution of Amphipods (*a*), of Euphausiids (*b*) and of composite plankton (*c*) in fractioned samples ⊙ compared with the theoretical curve.

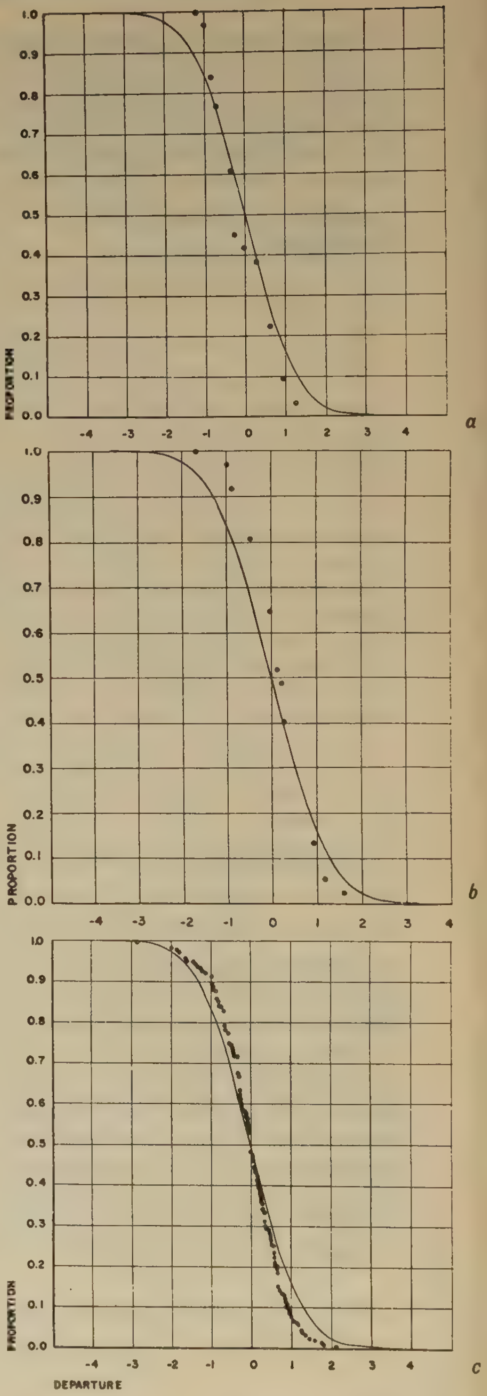

Fig. 5. Departure, $\frac{x}{\sigma}$ distribution of Amphipods (*a*), of Euphausiids (*b*) and of composite plankton (*c*) in fractional samples ⊙ compared with the normal or Gaussian theoretical curve.

The satisfactory agreement of these observed and theoretical frequencies confirms the previous conclusion that the errors are random. Finally, for each kind of plankton, $\sum_{i=1}^{n} \frac{2 S_i^2}{\sigma^2} = \chi^2$, was computed where n, the number of entries is also the number of degrees of freedom. This is an index of the range of the differences $(L-R)$. The larger this value of χ^2, obtained from a given number of entries n, the smaller is the probability that it could result from chance. This probability can be found directly from χ^2 tables. The results for each kind of plankton are as follows:

Kind of Plankton	χ^2	n	Probability
Amphipods	25.1	31	0.77
Chaetognaths	37.1	37	0.47
Copepods	35.4	37	0.58
Decapod larvae	28.9	32	0.31
Euphausiids	32.9	37	0.66
Larvaceans	19	26	0.84

Accordingly, in all cases the probability is so large that the observed range in values $(L-R)$ can be regarded as a result of random errors.

Since the foregoing tests of randomness are well satisfied, the errors will be assumed to arise from chance combinations of random errors, without appreciable bias.

First a theoretical relation will be derived between the differences $(L-R)$ in volume measurements, and the differences between the initial volume V_0 and its estimated value $V_m = 2^m L_m$. Denote by r_1, the left-hand portion of V_0 in first fraction, and by r_2 the portion of $V_0 r_1$ in the second fraction, etc. Then $V_m = 2^m r_1 r_2 r_3 \ldots r_m V_0$, where r_i is intended to be $\frac{1}{2}$, but is subject to accidental errors.

Expressing r_i in terms of L_i,

$$V_m = 2^m \frac{L_1}{V_0} \cdot \frac{L_2}{V_{0/2}} \cdot \frac{L_3}{V_{0/4}} \cdots \frac{L_m}{V_{0/2}\, m-1} \cdot V_0 = L_1 X L_2 X L_3 \ldots X L_m X (B)$$

where $\frac{L_i}{V_{0/2}\, i-1}$ is approximately $\frac{1}{2}$; and B is a constant.

The general law of the propagation of errors of a product, $u = a\,x\,y\,z$, is $\left(\frac{\sigma_u}{u}\right)^2 = \left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 + \left(\frac{\sigma_z}{z}\right)^2$, where a is a constant factor. Applying this law to the expression for V_m, gives

$$\frac{\sigma_{V_m}{}^2}{V_m{}^2} = \frac{\sigma_{L_1}{}^2}{L_1{}^2} + \frac{\sigma_{L_2}{}^2}{L_2{}^2} + \frac{\sigma_{L_3}{}^2}{L_3{}^2} + \ldots \frac{\sigma_{L_m}{}^2}{L_m}.$$

If each value $\frac{\sigma_{L_i}{}^2}{L_i{}^2}$ is a constant, $\frac{\sigma_{L_1}{}^2}{L_1{}^2}$, $\frac{\sigma_{V_m}{}^2}{V_m{}^2}$ would equal $m \frac{\sigma_{L_1}{}^2}{L_1{}^2}$, which increases in proportion to the number of fractions taken. However, when values of $\frac{\sigma_{V_i}^2}{V_i^2} = \frac{2\,S_i^2}{a^2}$, where $a = \frac{L_i + R_i}{2}$, were plotted on a vertical scale against a, on Log-log paper, the points determined a sloping straight line, indicating a decreasing function of a. The fit of a straight line to the points was much improved by averaging values of $\frac{2\,S_i^2}{a^2}$ in groups according to successive size intervals of a. From this diagram it was found that the empirical equation $\frac{\sigma_V^2}{V^2} = \frac{.028}{\sqrt{V}}$ expressed the relation quite accurately.

Accordingly, assume the general law $L_i^t \frac{\sigma_{L_i}^2}{L_i^2} = \lambda$, where t and λ are constants, then $\frac{\sigma_{L_i}^2}{L_i^2} = \frac{\lambda}{L_i^t}$, and the general equation

$$\frac{\sigma_{V_m}^2}{V_m^2} = \left\{\frac{\sigma_{L_1}^2}{L_1^2} + \frac{\sigma_{L_2}^2}{L_2^2} + \frac{\sigma_{L_3}^2}{L_3^2} + \ldots + \frac{\sigma_{L_m}^2}{L_m^2}\right\} =$$

$$\left\{\frac{\sigma_{L_1}^2}{L_1^2} + \left(\frac{L_1}{L_2}\right)^t \frac{\sigma_{L_1}^2}{L_1^2} + \left(\frac{L_1}{L_3}\right)^t \frac{\sigma_{L_1}^2}{L_1^2} + \ldots + \left(\frac{L_1}{L_m}\right)^t \frac{\sigma_{L_1}^2}{L_1^2}\right\}$$

reduces to

$$\left\{1 + \left(\frac{L_1}{L_2}\right)^t + \left(\frac{L_1}{L_3}\right)^t + \ldots + \left(\frac{L_1}{L_m}\right)^t\right\} \frac{\sigma_{L_1}^2}{L_1^2}$$

$$\{1 + (2^t) + (2^t)^2 + (2^t)^3 + \ldots + (2^t)^{m-1}\} \frac{\sigma_{L_1}^2}{L_1^2}.$$

But for volumes, $\frac{\sigma_{L_1}^2}{L_1^2} = \frac{.028}{\sqrt{V_0/2}} = \frac{.028}{\sqrt{V_0}}\sqrt{2}$ and $t = \frac{1}{2}$.

Therefore

$$\frac{\sigma_{V_m}^2}{V_m^2} = \frac{.028}{\sqrt{V_0}}\{\sqrt{2} + (\sqrt{2})^2 + (\sqrt{2})^3 + \ldots + (\sqrt{2})^m\} = \frac{.028}{\sqrt{V_0}} F_V(m).$$

Values of the factor $F_V(m)$ are as follows:

$m =$	1	2	3	4	5
$F_V(m) =$	$\sqrt{2}$	$2 + \sqrt{2}$	$2 + 3\sqrt{2}$	$6 + 3\sqrt{2}$	$6 + 7\sqrt{2}$
$=$	1.414	3.414	6.243	10.243	15.900

$m =$	6	7	8	9
$F_V(m) =$	$14 + 7\sqrt{2}$	$14 + 15\sqrt{2}$	$30 + 15\sqrt{2}$	$30 + 31\sqrt{2}$
$=$	23.900	35.213	51.213	73.840

This table can be verified and extended by means of the general formula

$$F_V(m + 1) = F_V(m) + 2^{\frac{m+1}{2}}.$$

The test series of volume measurements are presented in Table I, and the computations of $\frac{\sigma_{V_m}^2}{V_m^2}$ are presented in Table II. The values computed by the direct method using V_m and the observed values of V_0 are listed in next to the last line. The theoretical values $\frac{.028}{\sqrt{V_0}} F_V(m)$ are listed in the last line for comparison. The theoretical results are shown by the curve of Fig. 6, and the values obtained by the direct computation are shown by the points ⊙. The general agreement between the points and the curve confirms the theory.

Table I. *Initial Volume and successive Left and Right Fractions (each left portion was fractioned).*

Initial	*C*	*D*	*E*	*F*	*G*	*H*	*I*
Volume Fractions	281	75	78	84	127	84	97
$1/2$	*L* 145	28	50	40	57	41	51
	(*R* 136)	(47)	(28)	(44)	(70)	(43)	(46)
$1/4$	*L* 75	16	22	21	30	20	23
	R 69	16	24	21	27	21	24
$1/8$	*L* 31	8	12	11	16	12	12
	R 36	8	12	11	15	11	12
$1/16$	*L* 19	4	5	7	[7.5]	6	5
	R 18	5	6	7	counted	7	7
$1/32$	*L* 9	[2.25]	4	3		[3.25]	[3.25]
	R 10	counted	4	4		counted	counted
$1/64$	*L* 6		[2]	[1.75]			
	R 6		counted	counted			
$1/128$	[3] counted						

Volumes in square bracket [ ] are estimated portions at which counts of organisms were made and are not used until later, in the analysis of counts.

In the direct computation of the variance, $\sigma_{V_m}^2$, sums of the squares of the departures from V_0 were divided by k, the number of values, because V_0 is given, independently of values of V_m. The mean of the values of V_m can be used instead of V_0, but the sum of the squares of the departures from the mean must be divided by $k - 1$.

The error in the estimated number of plankton in the initial sample depends upon the variability of the density, or number of particles per cubic cm of the sample as well as the volume. Let $C_m{}^* =$ the count in the mth fraction and let $D_m{}^* =$ the density of the plankton in this fraction. Then $C_m^* = D_m^* L_m$, where L_m equals the volume of the left hand mth fraction. Then, using the law for the (c. v.)^2 of a product.

$$\frac{\sigma_{C_m*}^2}{(C_m^*)^2} = \frac{\sigma_{D_m*}^2}{(D_m^*)^2} + \frac{\sigma_{L_m}^2}{L_m^2},$$

where the last term pertains to the volume, and has already been considered. The measured values of L_m differ from their intended amount, $V_0\left(\frac{1}{2}\right)^m$, by random errors. Denote the number of plankton in this constant volume by

$$C_m = D_m^* V_0\left(\frac{1}{2}\right)^m.$$

Then

$$\frac{\sigma_{D_m*}^2}{(D_m^*)^2} = \frac{\sigma_{C_m}^2}{C_m^2}$$

and

$$\frac{\sigma_{C_m*}^2}{(C_m^*)^2} = \frac{\sigma_{C_m}^2}{C_m^2} + \frac{\sigma_{L_m}^2}{L_m^2}.$$

Regarding the term $\frac{\sigma_{C_m}^2}{C_m^2}$, the volume $2V_0\left(\frac{1}{2}\right)^m$ can be considered to contain $D^*\, 2\, V_0\left(\frac{1}{2}\right)^m = n$ individuals, distributed between the two halves of the volume according to the binomial distribution, $(q+p)^n = q^n + n\,q^{n-1}\,p + \frac{n\,(n-1)}{2}\,q^{n-2}\,p^2 + \ldots + p^n$, where $(q+p) = 1$. On the basis of chance q^n is the probability that all of them will be in the left-hand half, and none in the right-hand half, and p^n is the probability that all would be in the right-hand half. Thus, any term of the series is the probability that the exponent of q would be the number of particles in the left-hand half of the volume. Although, such particular consequences of the assumed distribution are helpful in understanding the frequency law, it is necessary to consider certain general properties of the distribution in order to determine the $(C\,V)^2$, and obtain results that apply readily to any number of individuals. The binomial series contains $(n+1)$ terms, the mean value of the number is $n\,p$, and its variance is $n\,p\,q$. Therefore, the $(C\,V)^2 = \frac{n\,p\,q}{(n\,p)^2} = \frac{q/p}{n} = \frac{q/p}{D^*\,2\,V_0\,(^1/_2)^m} = \frac{\sigma_{C_m}^2}{C_m^2} = \frac{q/p}{C_m},$

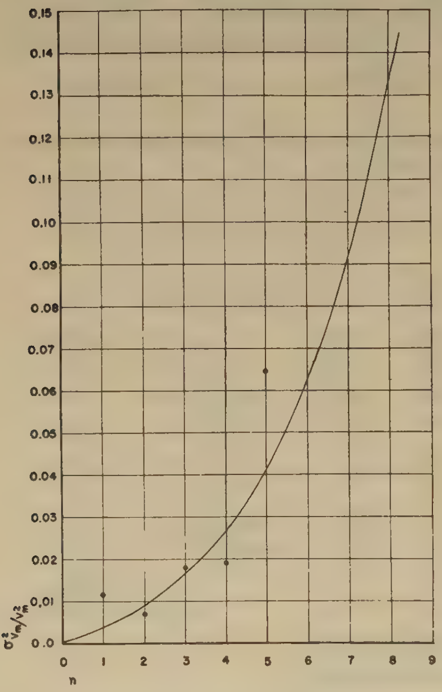

Fig. 6. $\sigma_{V_m}{}^2/V_m{}^2$ computed directly ⊙ compared with theoretical curve.

Table II. *Initial Volumes, V_m of each series, estimated from the Indicated Fraction.*

Fraction Series	$^1/_2$	$^1/_4$	$^1/_8$	$^1/_{16}$	$^1/_{32}$	Given Initial Volume V_0	Square of Initial Volume V_0^2
C	2 × 145 = 290	4 × 75 = 300	8 × 31 = 248	16 × 19 = 304	32 × 9 = 288	281	78961
D	2 × 28 = 56	4 × 16 = 64	8 × 8 = 64	16 × 4 = 64		75	5625
E	2 × 50 = 100	4 × 22 = 88	8 × 12 = 96	16 × 5 = 80	32 × 4 = 128	78	6084
F	2 × 40 = 80	4 × 21 = 84	8 × 11 = 88	16 × 7 = 112	32 × 3 = 96	84	7056
G	2 × 57 = 114	4 × 30 = 120	8 × 15 = 120			127	16199
H	2 × 41 = 82	4 × 20 = 80	8 × 12 = 96	16 × 6 = 96		84	7056
I	2 × 51 = 102	4 × 23 = 92	8 × 12 = 96	16 × 6 = 96		97	9409
					Totals . . .	826	130383
					Means . . .	118	18620
					V_m^2 . . .	$(118)^2$	13920

(Comp.) (— Initial)	$(V_m - V_0)$	$(V_m - V_0)^2$	$(V_m - V_0)$	$(V_m - V_0)^2$	$(V_m - V_0)$	$(V_m - V_0)^2$	$(V_m - V_0)$	$(V_m - V_0)^2$	$(V_m - V_0)$	$(V_m - V_0)^2$
	9	81	19	361	— 33	1089	23	529	7	49
	— 19	361	— 11	121	— 11	121	— 11	121	0	0
	22	484	10	100	18	324	2	4	50	2500
	— 4	16	0	0	4	16	28	784	12	144
	— 13	169	— 7	49	— 7	49	0	0	0	0
	— 2	4	— 4	16	12	144	12	144	0	0
	5	25	— 5	25	— 1	1	— 1	1	0	0
Totals	— 2	1140	2	672	— 18	1744	53	1583	69	2693

Number of Entries = k	7	7	7	6	3		
$\Sigma (V_m - V_0)^2/k = \sigma_{V_m}^2$	163	96	249	264	898		
m	1	2	3	4	5	6	7
Direct Computation of $\sigma_{V_m}^2/V_m^2$ . . .	.0117	.0069	.0179	.01897	.0645		
Theoretical Computation of $\sigma_{V_m}^2/V_m^2$	.0036	.0088	.0161	.0264	.0410	.0618	.0908

where C_m equals the number in the portion fractioned last. It is therefore twice the number counted in the last fraction $= (C_2 + C_2)_m$. The value of the count $(C_2)_m$, found by splitting C_m, differs from the mean, $n\,p$ by random errors, and there may be a tendency to obtain greater than half of the number in either the left or the right sample. This would be a biased result, represented by $q \mp p$. The skewness of this distribution is $\alpha_3 = \frac{q-p}{\sqrt{n\,p\,q}}$ and accordingly decreases as n increases. The various coefficients for selected values of q and p, are given in the following table.

q	p	q/p	$\frac{q-p}{\sqrt{p\,q}} = \sqrt{n}\,\alpha_3$
.3	.7	.428	— .873
$^1/_3$	$^2/_3$	.500	— .707
.4	.6	$^2/_3$	— .408
.5	.5	1.000	0
.6	.4	1.500	.408
$^2/_3$	$^1/_3$	2.000	.707
.7	.3	2.333	.873
$^3/_4$	$^1/_4$	3.000	1.154
.8	.2	4.000	1.500
.9	.1	9.000	2.667

The skewness α_3 is found by dividing the last column by $\sqrt{n}$. Assuming perfect symmetry, $q = p = {}^1/_2$, and $\frac{\sigma_{C_m}{}^2}{C_m{}^2} = \frac{q/p}{C_m}$ reduces to $\frac{1}{C_m}$.

Accordingly, by reference to the general formula, page 512, the value of t would be 1 and the $(C\,V)^2$ of N_m would be

$$\frac{\sigma_{N_m}{}^2}{N_m{}^2} = (1 + 2 + 2^2 + \ldots + 2^{m-1})\,\frac{\sigma_{L_1}{}^2}{L_1{}^2}.$$

Therefore,

$$\frac{\sigma_{N_m}{}^2}{N_m{}^2} = \frac{1}{N_0}\,F_n\,(m),$$

where

$$\begin{array}{rccccccccc} m = & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ F_N\,(m) = & 1 & 3 & 7 & 15 & 31 & 63 & 127 & 255 & 511 \\ \Delta F_N\,(m) = & & 2 & 4 & 8 & 16 & 32 & 64 & 128 & 256 \end{array}$$

$$\Delta F_N\,(m) = F_N\,(m+1) - F_N\,(m) = 2^m.$$

$$\text{Also}\ \ F_N\,(m+1) = 2\left[F_N\,(m) + \frac{1}{2}\right].$$

These relations serve to check the numerical results listed and to extend the table, if desired.

The foregoing results can be combined into the following theoretical formula for computing the $(C\,V)^2$ of N_m.

$$\frac{\sigma_{N_m}^{\,2}}{N_m^{\,2}} = \frac{.028}{\sqrt{V_0}} F_V(m) + \frac{1}{N_0} F_N(m).$$

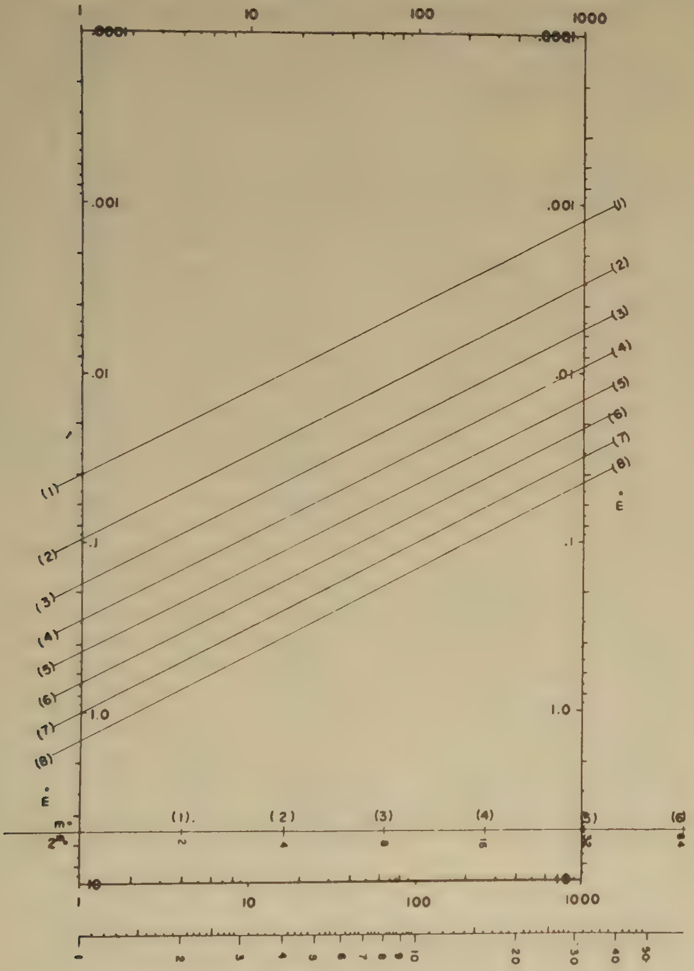

Fig. 7. Log-log diagram for computing $\frac{.028}{\sqrt{V_0}} F_V(m)$ and log diagram for computing $N_m = 2^m\, C_m$.

In practice neither V_0 nor N_0 are known, but their estimated values V_m and N_m serve as satisfactory approximations.

This basic formula, adapted to practical use, with the aid of the tables of $F_V(m)$, and $F_N(m)$ is illustrated in Figs. 7 and 8 which can be used directly for graphical determinations of $\frac{\sigma_{N_m}^{\,2}}{N_m^{\,2}}$, as follows:

Enter the volume, L_m of the mth fraction, on the lowest horizontal scale of Fig. 7. The straight line determined by the volume of the mth fraction on the bottom scale and the point m on the horizontal scale of

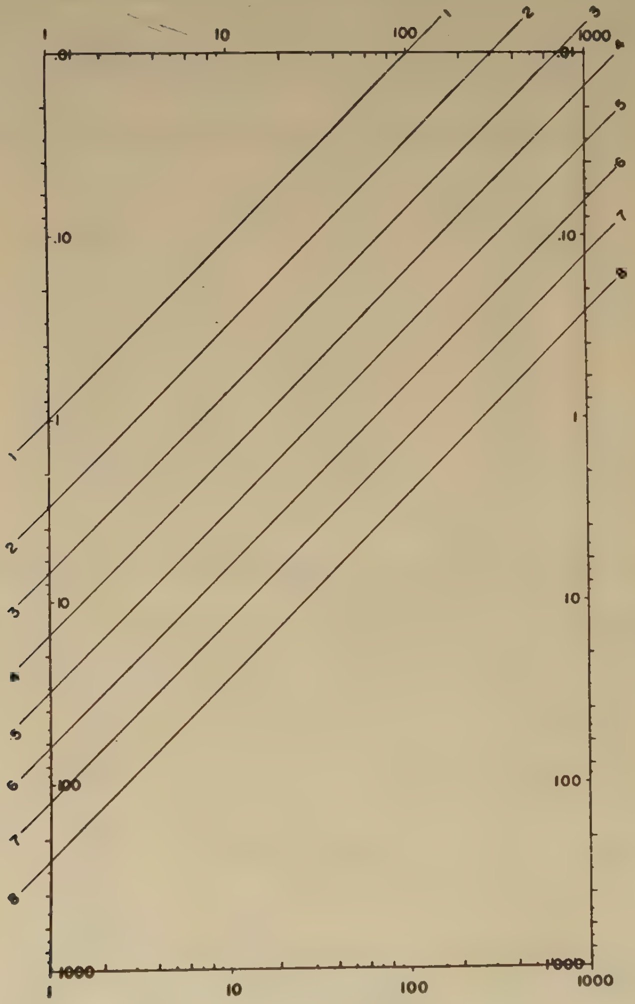

Fig. 8. Log-log diagram for computing $\frac{1}{N_0}[F_N(m)]$.

2^m intersects the middle horizontal scale at the value V_m, the estimated value of V_0. A vertical line through this point intersects the sloping line labeled m at a point on a horizontal line which intersects either vertical scale at the value of $\frac{\sigma_{V_m}^{2}}{V_m^{2}} F_V(m)$.

The straight line determined by the count of the mth fraction on the bottom scale of Fig. 7 and the point m on the horizontal scale of 2^m intersects the middle horizontal scale at the value of N_m, the estimated value of N_0. A vertical line through this point on the horizontal scale of Fig. 8 intersects the sloping line corresponding to m at a point whose height on either vertical scale is the value of $\frac{\sigma_{C_m}{}^2}{C_m{}^2} F_N(m)$.

Adding these two results gives the required theoretical value of $\frac{\sigma_{N_m}{}^2}{N_m{}^2}$.

Two contrasting plankton types, Amphipods and Euphausiids, were selected in order to test the foregoing formula. This involved the laborious task of direct counts of the six initial samples of each. Final fractions of $^1/_{16}$, $^1/_{32}$ and $^1/_{64}$ of the original had already been counted. In order to show the variability of the observations on these types, detailed tabulations have been prepared, Table III for the Amphipods and Table IV for Euphausiids. Actual counts are listed first for both the left-hand and right-hand proportions under the values of m. Values of $(C\,V)^2\,N_m$ next to the last line of Table III are averaged for each value of m. Theoretical values computed for each of the groups D to I were likewise averaged for the same values of m and entered in the last line. The upper theoretical curve of Fig. 9 was plotted from theoretical values averaged for each value of m. The points obtained by direct computation agree well with the curve.

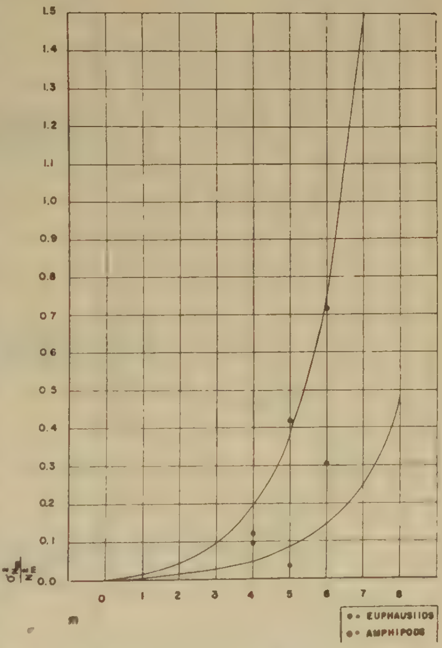

Fig. 9. $\sigma_{N_m}{}^2/N_m{}^2$ computed directly ○ compared with theoretical curve.

Following the same procedure for the Euphausiids, Table IV and the lower curve of Fig. 9 were obtained. Although the agreement of the points with the curve is not good, in detail, there is a general verification of the theory.

This statistical analysis of the performance of the plankton sample splitter shows it to be well adapted to the purpose of obtaining unbiased representative random samples of the initial net haul. The convenient methods developed for estimating the error of the sample should be of practical value to biologists engaged in quantitative plankton studies.

Table III. *Table of Counts and Computations of Amphipods.*

$m =$	*G* 4		*H* 5		*I* 5		*D* 5		*E* 6		*F* 6	
	L	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*
	23	30	1	1	5	2	14	18	0	1	2	3
	38	32	1	4	4	1	13	9	0	1	1	0
	17	28	4	0	3	6	8	10	1	0	2	4
	16	23	3	1	3	6	12	9	0	1	2	0
			2	3	5	8	8	3	0	2	2	4
									2	0	1	3

N_m = *Products of Counts L by* 2^m.

		368		32		160		448		0		128
		608		32		128		416		0		64
		272		128		96		256		64		128
		256		96		96		384		0		128
				64		160		256		0		128
										128		64
	4	1504	5	352	5	640	5	1760	6	192	6	640
Means . . .		376		70		128		352		32		107

N_0 =	414	44	137	300	43	128	
K =	4	5	5	5	6	6	
V_0 =	120	104	104	72	128	115	
$\sigma^2{}_{N_m}$ =	21 220	2090	900	9270	2512	1365	By direct computation
$(CV)^2{}_{N_m}$ =	.124	1.080	.048	.103	1.358	.083	
	.124		.410		.720		Values of $(CV)_{N_m}{}^2$ averaged with respect to m
	.195		.392		.757		Theoretical values of $(CV)_{N_m}{}^2$

Table IV. *Table of Counts and Computations of Euphausiids.*

m =	G 4		H 5		I 5		D 5		E 6		F 6	
	L	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*	*L*	*R*
	32	41	120	134	38	38	23	20	6	3	78	73
	34	43	138	144	46	55	38	25	3	5	80	63
	17	27	162	141	43	39	34	33	5	4	78	112
	17	16	129	124	64	54	34	28	1	4	84	71
			120	117	47	50	34	25	9	3	94	87
									11	1	81	60

N_m = *Products of Counts L by* 2^m.

	G	H	I	D	E	F
	512	3840	1216	736	384	4992
	544	4420	1472	1216	192	5122
	272	5184	1376	1089	320	4992
	272	4138	2048	1089	64	5366
		3740	1504	1089	576	6006
					704	5186
	4 1600	5 21322	5 7616	5 5219	6 2240	6 31664
Means . . .	400	4264	1523	1044	373	5277

	G	H	I	D	E	F	
N_0 =	454	3928	1515	940	294	5240	
K =	4	5	5	5	6	6	
V_0 =	120	104	104	72	128	115	
$\sigma^2_{N_m}$ =	19420	381358	78956	36879	53290	123700	
$(CV)^2_{N_m}$ =	.0944	.0247	.0344	.0417	.617	.0045	By direct computation
	.094		.034			.310	Values of $(CV)_{N_m}{}^2$ averaged with respect to m
	.047		.083			.147	Theoretical values of $(CV)_{N_m}{}^2$

The foregoing investigation of errors in laboratory apparatus suggests the desirability of at least a brief comment on errors and variability of net hauls. Towing a net at a selected level for a short time, say twenty minutes, provides a sample of floating material in a limited volume at that level and is usually accompanied by information about the chemistry and physics of the environment. Repeated collections of this kind can be so tabulated as to indicate the relation of the abundance of plankton to the environmental factors. An outstanding characteristic of such data is high variability, making it necessary to work with average values. Some indication of the minimum variability in abundance results from towing a pair of nets close together and comparing the catches in the right and left rets. In this case the volume of sea water containing the plankton would be nearly equal and could be assumed to be identical as regards environmental factors. However, according to experience a pair of such hauls is highly variable. The following typical results illustrate this variability.

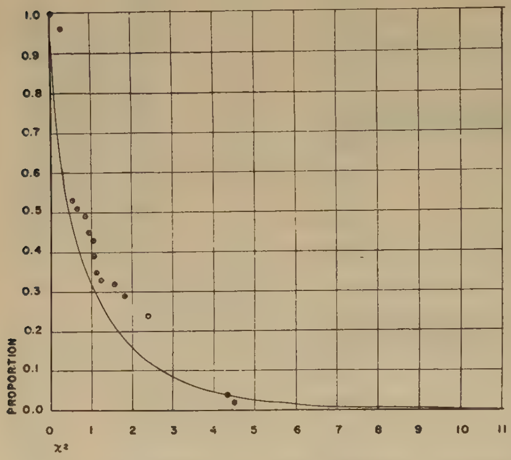

Fig. 10. χ^2 distribution of paired net hauls of *Sagitta bipunctata* compared with theoretical curve.

L	9	0	52	37	0	3	1	7
R	0	1	33	36	3	3	0	24

For a detailed description of a pair of closing nets used by the Scripps Institution for Biological Research, see Michael and McEwen (1916), p. 209–12. An analysis of a series of 51 pairs of such net hauls operated for fifteen-minute intervals from an anchored ship yield the following summarized results for Sagitta bipunctata. χ^2 values of the pairs followed the theoretical curve quite closely and the ratio of departures from the mean to the standard deviations agreed well with the normal law, Figs. 10 and 11. Randomness of the differences in catch of the paired nets is thus indicated.

About half of the values of the $(CV)^2$ exceeded 1, the most frequent values being 2, about 20 were $\eqslantless$ than 0.5. Arranging the counts $L + R = 2\,N$ into 10 groups according to increasing values of $2\,N$, averages of corresponding values of $\frac{\sigma_N{}^2}{N^2} = \dfrac{\dfrac{(L - R)^2}{2}}{\left[\dfrac{(L + R)}{2}\right]^2}$ were entered in the second line of the following table:

$2N$	1	2	3	4	5	6–7	9	10	17–18	32
$\frac{\sigma_N^2}{N^2}$	2	1.33	1.11	0.5	0.5	.18	.07	.32	.16	.6
$\frac{3}{2N}$	3	1.5	1.0	0.75	0.6	.46	.33	.30	.17	.09

If, as in the plankton splitter $2N$ organisms of any kind are considered to be distributed in the paired nets according to the expansion of the binomial $(q+P)^{2N}$, and perfect symmetry, $q=p$, is assumed, the value of $\frac{\sigma_N^2}{N^2}$ would equal $\frac{1}{2N}$. However, it was found that the directly computed values agreed better with $\frac{3}{2N}$, entered in the last line. This apparent discrepancy may be due to the observed tendency of organisms to occur in groups, which have a roughly uniform distribution. Thus the theoretical result $\frac{1}{2N}$ would pertain to groups rather than to individual organisms, and, there should be a factor equal to the average number per group. The following theoretical formulae relating the number of net hauls capturing n or more organisms to the average number of organisms per haul A, agree with artificial experiments in which an approach to uniformity is obtained by mixing.

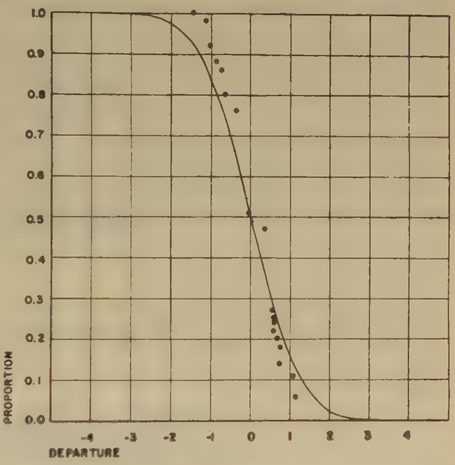

Fig. 11. Departure, $\frac{x}{\hat{\sigma}}$ distribution of *Sagitta bipunctata* compared with the normal or Gaussian theoretical curve.

n, Frequency,
1, $1-C^{-A}$,
2, $1-C^{-A}(1+A)$,
3, $1-C^{-A}\left(1+A+\frac{A^2}{2}\right)$.

However, according to McEwen (1929), for Zooplankton in the ocean, the value A computed from these formulae was of the order $^1/_5$ of the number actually counted. This indicated a roughly uniform distribution of groups containing several individuals. Thus the foregoing modification of the expression $\frac{1}{2N}$ by the factor of 3 would be reasonable.

Regarding the number of organisms in the net haul as a sample from the ocean, the value of $\left[\frac{\sigma_N^2}{N^2}\right]_0 = \frac{3}{2N}$ would have to be added

Table V. *Results of Combining Field and Laboratory Errors of Plankton Abundance.*

(1) Assumed Values of $2N_0$	(2) N_0	(3) $\frac{3}{(1)}$	(4) m	(5) Number in Counted Samples L_N	(6) $\frac{1}{2N_0}$	(7) $F_N(m)$ p. 516	(8) (7) × (6)	(9) $F_V(m)$ p. 512	(10) (9) $\frac{.028}{\sqrt{V_0}}$	(11) (8) + (10)	(12) (11) + (3) Combined Field & Laboratory Error
1					1.0						
2	1	1.5			.5						1.5
4	2	.75			.25						.75
8	4	.375			.125						.375
16	8	.188	0	8	.0625	0	0	0	0	0	.188
32	16	.094	1	8	.0312	1	.0312	1.41	.0039	.0351	.129
64	32	.047	2	8	.0156	3	.0470	3.41	.0095	.0565	.103
128	64	.023	3	8	.0078	7	.0546	6.24	.0175	.0721	.096
256	128	.012	4	8	.0039	15	.0585	10.24	.0286	.0871	.099
512	256	.0058	5	8	.0019	31	.0590	15.90	.0445	.1035	.109
1024	512	.0029	6	8	.0010	63	.0610	23.90	.0670	.128	.131
2048	1024	.00098	7	8	.0005	127	.0620	35.21	.0985	.160	.161
4096	2048	.00049	8	8	.00024	255	.0620	51.21	.1435	.204	.204
8192	4096	.00024	9	8	.00012	511	.0620	73.84	.207	.269	.269

to the value applying to the plankton splitter in order to obtain the proper composite error applying to quantitative researches.

The following hypothetical example shows the range of estimates of the composite error due to splitting the haul until the count was constant. The resulting $(CV)^2$ varied only from .188 to a minimum of .1 and a maximum of .269 for m ranging from 0 to 9 and N_0 ranging from 8 to 4096, according to Table V.

Discussion.

In choosing the seven plankton samples here used for statistical analyses, an attempt was made to select a series representing different community compositions as found in nature. This was done in order to test whether or not the kinds of organisms, and the relative abundance or sizes, might influence the results.

The ease with which it is possible to quickly identify the organisms present in a sample and to count their numbers is influenced by the composition of the sample at hand. Thus, large numbers of translucent doliolids or salps, for example, interfere especially with the analysis and counting of other translucent or transparent forms, such as larvaceans, small chaetognaths, certain copepods such as *Eucalanus*, and others. In routine counting, these difficulties may introduce some errors so that minumum counts may be recorded for such hyaline forms.

The presence of slime or stringy fragments from broken jellyfish, ctenophores, salps, heteropods, etc., which cause agglutinations or tangling, especially of spinaceous forms, including some decapod larvae, the copepods such as *Euchaeta*, *Candacia* and others may be a source of discrepancies in splitting as well as counting. There was some agglutination in samples, C-5-901, B-18-40.100, and S-21-77.65, but these seem not to have interfered seriously.

Sample C-5-901 contained a large number of pteropods which because of their calcareous shells, precipitate quickly after the sample has been shaken. However, the splitting and counting of the sample appears not to have been much influenced by this factor.

While the tables and graphs give the relative numerical abundance of the different animals counted, it is useful to supplement these data with the following partial analysis relative to the kinds and size-ranges of the most significant of these animals, together with the approximate wet volume composition of the samples.

C-5-901

Copepods: length 2–8 mm.
Eucalanus bungii 58%; *Calanus finmarchicus* 13%; *Metridia lucens* 10%; Others 19%.
Euphausiids: length 4–10 mm.
Euphausia pacifica 82%; *Thysanoëssa gregaria* 18%.
Chaetognaths: length 5–10 mm 90%; 11–15 mm 10%.
Amphipods: length 2–7 mm.
Decapod larvae (Macruran): length 10–15 mm.
Pteropods *(Limacina)*: length 1–2.5 mm.
Volume composition: pteropods 33%; euphausiids 5%; copepods, and others 62%.

B-18-40.100

Copepods: length 1.5–7 mm.
Eucalanus bungii 62%; *Calanus finmarchicus* 19%; *Clausocalanus arcuicornis* 9%; Others 10%.
Euphausiids: length 3–5 mm.
Chaetognaths: length 4–10 mm 93%; 11–15 mm 7%.
Amphipods: length 1–10 mm.
Annelids: length 3–10 mm.
Tomopteris 39%; syllid 61%.
Doliolids: length 5–12 mm.
Volume composition: salps and doliolids 93%; others 7%.

P. 18-120.35

Copepods: length 1.5–4 mm.
Calanus finmarchicus 88%; *Clausocalanus arcuicornis* 5%; *Acartia spp.* 4%; others 3%.
Euphausiids *(Euphausia pacifica)*: size 5–11 mm.
Chaetognaths: length 6–10 mm 62%; 11–15 mm 38%.
Amphipods: length 2–6 mm.

Decapod larvae: length 5–15 mm.
Volume composition: copepods 90%; euphausiids, and others 10%.

C-18-70.55

Copepods: length 1.5–6 mm.
Calanus finmarchicus 71%; *Metridia lucens* 10%; *Sappharina* 8%; Others 11%.
Euphausiids: length 10–20 mm.
Euphausia pacifica 5–10 mm 59%; 11–15 mm 38%; 16–21 mm 3%.
Chaetognaths: length 10–15 mm 60%; 16–22 mm 40%.
Amphipods: length 2–5 mm 75%; 10–15 mm 25%.
Doliolids: length 6–13 mm.
Decapod larvae: length 4–10 mm.
Volume composition: doliolids 93% of the sample, copepods and others 7%.

S-21-77.65

Copepods: size, 1.5–8 mm.
Calanus finmarchicus 34%; *Euchirella pulchra* 30%; *Pleuromamma spp.* 19%; Others 17%.
Euphausiids: size, 7–10 mm 85%; 11–15 mm 11%; 16–22 mm 4%.
Thysanoëssa gregaria 71%; *Euphausia spp.* 22%; *Stylocheiron longicorne* 7%.
Chaetognaths: size, 10–30 mm.
Amphipods: size, 4–8 mm.
Salps, length 15–30 mm.
Doliolids, length 10–15 mm.
Volume composition: very mixed.

H-21-117.35

Copepods: length 1.5–7 mm.
Calanus finmarchicus 30%; *Pleuromamma spp.* 29%; *Eucalanus bungii* 17%; Others 24%.
Euphausiids: length, 5–10 mm 13%; 11–15 mm 21%; 16–20 mm 66%.
Euphausia pacifica 82%; *Thysanoëssa spinifera* 18%.
Chaetognaths: length 2–10 mm.
Amphipods: length, 2–8 mm.
Decapod larvae (Mostly zoea): length 4–10 mm.
Volume composition: euphausiids (10–20 mm) 60%; smaller euphausiids, copepods, etc. 40%.

Cape Arago sample

Copepods: length 2–4 mm (make up about 98% of volume).
Calanus finmarchicus 87%; others 13%.
Euphausiids *(Euphausia pacifica)*: length, 5–8 mm.
Chaetognaths: length 5–10 mm 80%; 11–15 mm 20%.
Decapod larvae (Macruran): length, 5–7 mm.
Volume composition: copepods 98%.

In the study of marine plankton as in many other branches of marine science, it is not possible to make direct visual observations on the populations as can frequently be done when studying the intertidal benthic communities. We are, therefore, dependent upon mechanical devices for the purpose of collecting representative samples. One necessary step in the designing and application of adequate collecting gear is an appreciation of the degree of variability of distribution.

The towing of two identical nets side by side simultaneously provides information on the randomness of distribution within relatively narrow confines or swarms. Over wider areas, greater differences often occur from station to station. These may indicate swarming or the abrupt passing from one environmental biotope into another.

It is precisely these differences that we must be able to detect in order to evaluate the factors, biological, chemical or physical that influence organic production, concentration and utilization. Thus the biologist is greatly aided by the engineering ingenuity that provides not only the most efficient types of collecting gear but also laboratory aids in facilitating the study of the samples.

The concentration of plankton within certain areas or into swarms may in part result from organic factors but it is appropriate to stress here the need of the biologist for physical data on current systems, water masses, etc. in order that he may better understand the variability of distribution as found in nature. In this connection the works of Dr. DEFANT in furthering the studies of physical oceanography have assumed a great biological significance that is widely appreciated in all fields of biological oceanography.

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An Acidogenic Carotenoid in a Bathypelagic Nemertean Worm*

CERTAIN brightly coloured littoral nemerteans contain carotenoids, and it is likely that most deep-sea species of similar coloration likewise store this class of biochrome[1].

Recently, there arose a rare opportunity to examine briefly the red-orange pigment from three freshly collected specimens of *Nectonemertes mirabilis* Verrill (one immature male and two females, 30–34 mm. long and 5 mm. wide). These were taken in a depth haul from 1,200 m. to the surface in the Santa Barbara Passage off the coast of Southern California by Dr. N. T. Mattox at the Allen Hancock Foundation, and were presented to Prof. W. R. Coe of the Scripps Institution, who identified them as members of this widely distributed species, usually encountered at depths from 500 m. down, in the North and the South Pacific Ocean.

The specimens, fixed in dilute formalin, then preserved in 70 per cent ethanol, were examined within a week after capture. The deep red-orange pigment was concentrated in oil droplets in the digestive diverticula. In view of the unlighted habitat and the microcrustacean diet of this worm, it was of special interest to learn whether, as in numerous other marine carnivores, its richly stored pigment might belong to the oxygenated carotenoids[1].

The preserved worms had lost none of their bright colour, but substitution of absolute ethanol readily leached the pigment out, imparting a red-orange colour to the solvent and leaving the animals quite pale. The pigment was completely epiphasic, migrating quantitatively from the alcohol into light petroleum to give a yellow solution. However, after an hour's exposure to warm ethanolic potassium hydroxide, the pigment showed quantitative hypophasic behaviour, thus reflecting the absence of carotenes and the original presence of esterified xanthophylls. Dilution effected the migration of a trace of yellow pigment into the petroleum, while the more copious red component now separated as a potassium salt at the liquid interface. In its preferential solubility in alcohol, and in its reversible transference from alkaline or neutral alcohol to petroleum,

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* Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 690.

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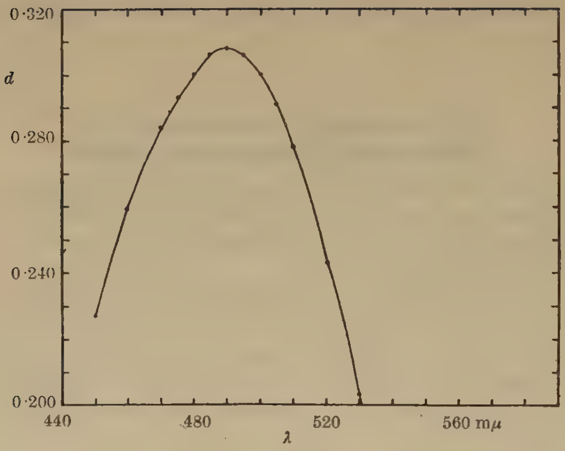

Absorption curve of acidic carotenoid derived from an ester occurring in *Nectonemertes mirabilis* Verrill

the yellow component behaved like a neutral xanthophyll. Its quantity was insufficient for further study.

The red interfacial salt was washed with additional petroleum and was then readily dissolved in this solvent containing a little acetic acid. The yellow petroleum solution displayed, on shaking with water, the transient pinkish emulsion which characterizes other acidogenic carotenoids, such as astacene and metridioxanthin[2]. The acid-free petroleum solution was evaporated in an inert atmosphere and the deep orange residue was dissolved in redistilled pyridine (b.p. 114–116° C.). This red-orange solution exhibited a single, discrete absorption peak whose steep, symmetrical shape and maximum at 490 mμ differentiated it from astaxanthin or its artefact, astacene, which show a less sharp maximum at 500 mμ in the same solvent (Beckman photoelectric spectrophotometer; see accompanying figure). In its spectrum the nemertean pigment recalls a similar acidogenic carotenoid from the marine shrimp *Hippolyte*[3] and another from the anemone *Metridium*[4].

Evidently this deep-sea pelagic ribbon-worm owes its bright red-orange colour to the presence of an acidogenic carotenoid ester, related to but not identical with astaxanthin. The principal carotenoid and the accompanying traces of esterified neutral xanthophyll doubtless originate from the animal's consumption of planktonic crustaceans and other pelagic fauna. The finding of rich stores of oxygenated carotenoids, unaccompanied by any carotene hydrocarbons, adds to the growing list of xanthophyllselecting marine carnivores[1], a widely occurring species the habitat of which is limited to great oceanic depths.

I acknowledge the generosity and help of Prof. Wesley R. Coe, and the welcome co-operation of Dr. Norman Millott in conducting the spectroscopic examination.

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Nov. 30.

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691

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High-Frequency Titration of Micro Quantities of Chloride and Sulfate

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AS ONE method of studying the shallow marine sediments of the northern Gulf of Mexico, chloride and sulfate ions are being determined in the interstitial water. Some restriction on the technique results from the samples being often as small as 0.3 or 0.4 ml. in which the total quantities of chloride and sulfate do not exceed 5 and 1 mg., respectively. Furthermore, as the water is often muddy, the usual turbidimetric methods of analysis are impractical.

The titration of sulfate with the help of a high-frequency oscillator has been found successful for quantities of sulfate as low as 0.5 mg. (*4*). The method is generally applicable for precipitation titrations. Jensen (*2*) titrated for the chloride in potassium chloride by using silver nitrate and silver acetate solutions and compared the end points. He found that silver acetate gave a much sharper end point. Jensen and Parrack (*3*) also found that the sharpness of the end points depends on the "nonpolarity" of the solvent. For some titrations, they used benzene with enough methanol to maintain solubility and found much sharper end points. All these results indicate that reduced degrees of dissociation bring about sharper end points.

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Silver acetate and barium acetate have been used as precipitating agents in the series of experiments to be described. The dielectric constant of the solvent, water, was lowered by various proportions of dioxane, which was chosen for this purpose because it has a dielectric constant as low as benzene and is miscible with water in all proportions. The author has been able to determine quantities as low as 0.5 ± 0.01 mg. of chloride and 0.15 ± 0.003 mg. of sulfate with a maximum variation of 2% between duplicate runs. Since the precipitants do not interfere with each other, it was possible to determine sulfate and chloride ions one after the other in the same sample and in the same titration cell.

APPARATUS AND REAGENTS

A Model V chemical oscillometer manufactured by E. H. Sargent and Co. was used for the titrations. Four titration cells with approximately the same cell constants were supplied with the instrument.

Specially constructed syringe-type micropipets, calibrated to the desired volume, were used for pipetting the samples, and Gilmont ultramicroburets were used for the titrations.

All reagents used in this series of experiments were Baker analyzed quality with the exception of dioxane, which was technical grade, and silver acetate, which was prepared in this laboratory.

PROCEDURES

Standardization and Calibrations. All volumetric apparatus was calibrated by weighing the water delivered. The pipets were found to have a maximum variation of ±0.2%. The total capacity of the Gilmont ultramicroburets was 1.0000 ± 0.0001 ml. in each case.

Sulfuric acid was standardized acidimetrically against sodium borate decahydrate as a primary standard. Silver acetate solutions were standardized against potassium chloride by the Mohr method, and barium acetate solutions was standardized gravimetrically.

Analytical Procedure. About 0.3 ml. of the sample was accurately pipetted with a calibrated pipet into a flask and diluted with water. A drop of methyl red indicator was added to the solution, which was then acidified with 0.1*N* acetic acid and heated to boiling. After cooling to room temperature, it was transferred to a titration cell and 40 ml. of dioxane was added. Enough water (about 60 ml.) was added to bring the level in the cell to half an inch above the metal ring of the cell and then a drop at a time was added until the dial reading was brought up to between 600 to 700 units, so that a titration could be completed by turning the dial alone while no changes of the setting of the switches on the left would be necessary.

For sulfate, seeding the precipitate with barium sulfate crystals has been recommended (*1, 4*); this was found unnecessary.

CALCULATION OF END POINT

The usual method of obtaining the end point with a Model V oscillometer has been to plot the dial readings which relate the dielectric constant of the solution to the volume of reagent used. The end point is obtained graphically from either one of the three possibilities: a true minimum point, the intersection of two curves, and an inflection point. The case of the end point occurring at an inflection point may be disregarded because by using the proper ratio of dioxane-water mixture, a minimum point can usually be obtained. Sometimes the titration curves are so steep that the end point is really the intersection of two curves. In these cases one may assume that the intersection point is the minimum of a continuous curve. Unless very accurate results are necessary, it is generally sufficient to assume the minimum point exists.

For a minimum point, $\Delta D/\Delta V$ is zero. If $\Delta D/\Delta V$ is plotted as a function of V, the portion of the curve between the points where $\Delta D/\Delta V$ changes from negative to positive assumes a straight line. By means of the regular algebraic formula for a straight line, one can simply calculate the value of V for which $\Delta D/\Delta V$ is zero. Take the data of run II in Table I, and let V be x and $\Delta D/\Delta V$ be y; then,

$$x_1 = 0.100 \text{ and } x_2 = 0.110$$

and

$$y_1 = -300 \text{ and } y_2 = 400$$

Substituting these values into the usual formula for a straight line:

$$(x - 0.100)/(0.100 - 0.110) = (y - 300)/(-300 - 400)$$

Solving for x for $y = 0$, one obtains $x = 0.1043$, which is the end point.

Table I. Standardization of Barium Acetate by Oscillometer

(Against 0.2772 ml. of 0.05283*N* H_2SO_4 soln.)

Run I					Run II		
V	ΔV	D	ΔD	$\Delta D/\Delta V$	D	ΔD	$\Delta D/\Delta V$
0.090	0.01	22,785	−10	−1,000	23,120	−10	−1,000
0.100	0.01	22,783	−2	−200	23,117	−3	−300
0.110	0.01	22,786	3	300	23,121	·4	400
Vol. at end point, ml.			0.1040			0.1043	
Normality $Ba(C_2H_3O_2)_2$			0.1408			0.1404	
Variation from gravimetric data (0.1405*N*), %	0.21					0.07	

RESULTS

Barium acetate solution was first standardized by a gravimetric method and then checked with the oscillometer by titrating against standard sulfuric acid. The end points of these titrations were calculated algebraically according to the method described. The data pertinent to the calculation are shown in Table I.

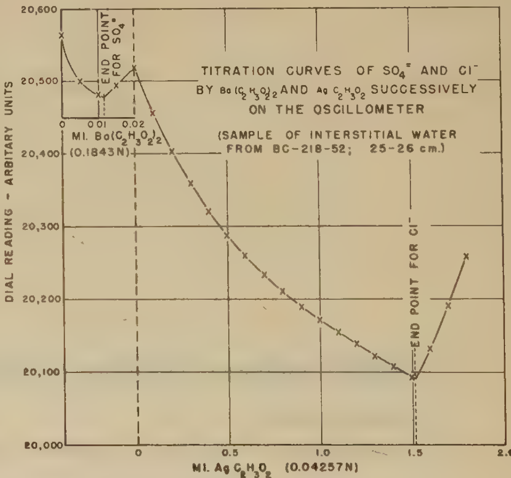

Figure 1. Typical Titration Curve

Silver acetate solution was first standardized against weighed amounts of potassium chloride by the Mohr titration method. A standard potassium chloride solution was used as the sample and titrated with the silver acetate solution by using the oscillometer. Portions of 0.2772 ml. of 0.4763*N* potassium chloride solution were titrated and a comparison of the results is given in Table II.

Table II. Standardization of Silver Acetate by Oscillometer Compared with Mohr Method

(Normality of silver acetate soln. = 0.05342*N*)

Run number	I	II
Volume at end point, ml.	2.41	2.42
Normality $AgC_2H_3O_2$ soln.	0.05354	0.05332
Variation from Mohr method, %	0.23	0.20

Table III. Analysis of Sea Water

	SO_4^{--} Present, Mg.	SO_4^{--} Found, Mg.	Error, %	Cl^- Present, Mg.	Cl^- Found, Mg.	Error, %
1	0.7946	0.7905	0.49	4.063	4.063	0.10
2	0.7946	0.8008	0.80	4.063	4.012	1.4
3	0.7946	0.7977	0.40	4.063	4.080	0.50
4	0.7946	0.7863	1.2	4.063	4.076	0.40
5	0.1844	0.1840	0.22	1.339	1.341	0.15
6	0.1844	0.1831	0.71	1.339	1.336	0.22
7	0.1476	0.1470	0.41	1.072	1.073	0.10
8	0.1476	0.1456	1.35	1.072	1.074	0.19
9	0.1476	0.1451	1.69	1.072	1.070	0.19
10	0.0738	...	...	0.5358	0.5360	0.19

A sea-water sample having a chlorinity of 18.59 parts per thousand and a sulfate content of 2.56 parts per thousand was analyzed by the procedure prescribed. More dilute samples of known chloride and sulfate contents were prepared by diluting the standard sea water and analyzing as before. The results, shown in Table III, indicate acceptable accuracy to as low a sulfate content as 0.15 mg.

When the sulfate content is lower than 0.1 mg. the method is not sensitive enough. The difficulty, however, can be overcome by adding a definite volume of a sodium sulfate solution corresponding to a definite volume of the standard barium acetate solution and then titrating to the end point. The sulfate content was calculated from the difference between the total volume of acetate used and the volume equivalent to the sulfate added. A typical titration curve is shown in Figure 1.

ACKNOWLEDGMENT

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MARINE GEOCHEMISTRY 1. CHEMICAL SCAVENGERS OF THE SEA[1]

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ABSTRACT

The ability of the hydrated oxides of manganese and iron to adsorb ions from solution (scavenging) is considered in relation to some problems in marine geology, chemistry, and biology. In the ferruginous sediments of the Pacific Ocean, iron oxides are accompanied by titanium, cobalt, and zirconium in amounts proportional to the iron content. Similarly, copper and nickel are linearly related to the manganese content. These observations are explained on the basis of scavenging. An electrochemical theory for the formation of manganese nodules is presented. Marine sediments are classified on the basis of the geosphere in which the solid phases originate. The distribution of certain ionic species in sea water between the solid and aqueous phases is considered on the basis of scavenging and co-ordination compound theory. The concentration of minor elements by members of the marine biosphere is explained either by the direct uptake of the element or by the uptake of iron or manganese oxides with the accompanying scavenged element.

The term "scavenger" in biology refers to certain predacious animals feeding upon carrion or detritus; but to the chemist it has an entirely different, but well-defined, meaning. Precipitation processes involving noncrystalline particles encountered in the laboratory are not of a simple, homogeneous nature. For instance, if ferric hydroxide is formed and precipitated in a solution of a uranium salt, the UX_1 (thorium-234) is adsorbed to the iron-dispersed phase. The UX_1 in radioactive equilibrium with its parent-uranium may be present to less than one ten-billionth the concentration of the iron. Such adsorption of a microcomponent to a gelatinous or finely divided precipitate is called "scavenging," and the precipitating agent itself, in this case the iron hydroxide, is denoted as the "scavenger." Some precipitates, such as manganese dioxide, aluminum hydroxide, and iron hydroxide, are so efficient in such processes that they are used extensively to decontaminate aqueous solutions of certain ionic species (Cook and Duncan, 1952, p. 10).

The action of such scavengers is due largely to surface adsorption (Wahl and Bonner, 1951, p. 117), that is, the process depends upon the relationship between the charge and the size of the adsorbed ion and the charge and topographical character of the adsorbing surface. As the total surface area of any given dispersed phase increases, the amount of the microcomponents adsorbed likewise becomes larger. Since the electrical charge of the scavenging agent must be opposite to the charges of the ions adsorbed, the ionic species most effectively scavenged are those with the highest charge densities. Tracer ions that form insoluble compounds or strong complexes with the lattice ions of the precipitate are more efficiently adsorbed than those ions that do not. Further, as a rather general rule, the longer the solid phase is in contact with the solution containing the ions to be absorbed, the more efficient is the uptake, presuming no re-formation of the precipitate occurs.

The existence of hydrous oxides in the ocean waters should give rise to this same type of adsorption phenomenon so readily observed in the laboratory. The presence of iron hydroxide in particulate

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and/or colloidal form has been adequately demonstrated (Cooper, 1948; Goldberg, 1952). The erratic distribution of iron in the sea has been attributed to the random distribution of relatively large iron oxide or hydroxide particles in suspension; sampling techniques utilizing small volumes give rise to nonreproducible results. The concentration of iron in marine waters varies from about 1 to 100 μgm/liter. The greater portion of this iron must be in colloidal or other particulate forms, inasmuch as the solubility products of ferric and ferrous hydroxides will allow but 0.5 μgm/liter of iron as ionic species. The charge on the ferric hydroxide sols in sea water has been determined by Harvey (1937), and it was found to be electropositive. Iron hydroxide sols in marine waters, accordingly, would scavenge negatively charged ions.

TABLE 1

GEOCHEMICAL PROPERTIES OF SOME METALS

Metal	Weight Per Cent in Manganese Nodules	Weight Per Cent in Meteorites (Brown, 1949)	Abundance in Sea Water (μgm/Liter)	Ionic Radii of Doubly Charged Cations (6-Fold Co-ordination) (Ahrens, 1952)
Fe	6.18 –20.27	45.7	10–100	0.74
Mn	10.8 –24.15	0.19	1– 10	.80
Ni	0.16 – 1.15	3.51	0.5 (the Noddacks, 1940)	.69
Co	0.066– 0.71	0.26	0.1 (the Noddacks, 1940)	.72
Cu	0.17 – 1.81	0.013	4 (the Noddacks, 1940)	0.72

The manganese content of ocean water varies between 0.7 and 10 μgm/liter, or about one-tenth the magnitude of the range of iron concentration (Thompson and Wilson, 1935). Harvey (1949) found 0.7–1.0 μgm of manganese per liter in sea water collected off Plymouth. This manganese was considered to be ionic or in a particulate form soluble at a pH of 4.6. If the solutions were stored and any particles removed by sedimentation, the observed manganese content decreased to 0.0–0.25 μgm/liter. The hydrated oxides of manganese are negative sols (Rankama, 1950, p. 235) and hence in marine waters would be expected to collect positively charged ions.

The biogeochemical roles of iron and manganese in oceanographic phenomena should reflect any scavenging actions of their oxides. Hence the effects of such chemical behavior will be considered in relation to some problems in marine geology, chemistry, and biology.

PELAGIC SEDIMENTS

The origin of the abundant iron and manganese oxides in marine pelagic sediments and the accumulations of these oxides in nodules or coatings are of major importance in marine geology. With respect to the manganese nodules, the iron content is increased over a million fold with reference to sea water, while the manganese concentration is ten million times that of the oceans (table 1).

The manganese nodules are found in deep-sea dredgings, having spherical or oblate shapes, often formed about a nucleus of pumice, consolidated clay, shark's teeth, or the earbones of whales. The nodules are built up as concentric shells, and the rate of accumulation is reported to be of the order of 1 mm. per thousand years (Pettersson, 1943; Butler and Houtermans, 1950).

Any theory on the origin of these concretions must account for the following: (1) the energetics of their formation; (2) the fact that the ratio of iron to manganese varies about unity, whereas in the ocean water or in most pelagic clays this ratio is nearer 10 (Clarke, 1924; Revelle, 1944); (3) their gross composition; (4) their structure; and (5) their geographic occurrence.

A chemical study of these nodules would present direct evidence of scavenging action if the iron and manganese of these nodules originated from the suspended matter of sea water. Hence nodules collected from 11 locations in the eastern Pacific Ocean were subjected to chemical assay for the following elements: manganese, nickel, cobalt, copper, aluminum, phosphorus, iron, titanium, and zirconium (table 2). All analytical procedures employed a Beckman model DU spectrophotometer and are described in table 3. Samples of the nodules, free from any visible clay or foreign mineral grains, were brought into solution with hydrofluoric acid in a platinum crucible, after an initial pulverization in an agate mortar. The samples were heated to dryness on a sand bath and redissolved in 6 N hydrochloric acid solution. Then the hydrochloric acid solution was heated to dryness to remove the hydrofluoric acid. This last step was repeated twice. Finally, the residue was dissolved in 0.25 N hydrochloric acid solution, from which aliquots were taken for analyses.

Returning to the problem of nodule formation, the oceans, as the liquid phase, along with the particulate iron and manganese dispersed throughout these waters, may be considered as a chemical system. At a later time this system is observed with the manganese-iron concretions. This decrease in entropy demands the introduction to the system of energy which may be of three main types: gravitational, biological, or tidal.

The particulate iron and manganese particles, as a result of gravity, should settle uniformly to give a coverage of dispersed oxides over the ocean bottoms corresponding to their oceanic abundances. This is found to be the case in pelagic clays, as Clarke (1924) reports 6.71 per cent iron and 0.765 per cent manganese in a composite mixture of 51 samples.

The inadequacies of biological mechanisms to account for any large-scale concentrations of iron and manganese have already been pointed out by Pettersson (1945) and will be omitted in this presentation.

An electrochemical process is proposed for the concentration of nearly equal amounts of iron and manganese in nodules. Mass movements of the water near the ocean bottom have been postulated (Sverdrup, Johnson, and Fleming, 1946, p. 567–568) and evidenced from underwater photographs (Menard, 1952) and the lithology of deep-sea sediments. Since sea water is an electrical conductor, the motion of water masses parallel to the earth's horizontal component of its magnetic field will set up a potential gradient in a direction perpendicular to the ocean bottom. Any conducting surface superior to the ocean bed itself will then serve as an electrode. These electrodes are proposed as the cores for the accretion of the manganese and iron.

If the cause of these underwater currents is tidal, a reversal in the polarity of the ocean-bottom electrodes will result with a diurnal period. Since the manganese sols are negatively charged, they

TABLE 2

CHEMICAL ANALYSES ON 11 PACIFIC OCEAN MANGANESE NODULES (WEIGHT PER CENT)

No.	Fe	Mn	Fe/ Mn	Ni	Co	Cu	P	Al	Ti	Zr	Latitude	Longitude	Description
11...	12.0	13.5	0.89	0.21	0.15	0.49	0.38	0.94	0.89	0.013	40° 14′ N.	155° 52′ W.	Horizon nodule; 2,750 fathoms
12...	12.2	13.3	0.92	0.16	.12	0.49	0.22						
13...	9.16	10.8	0.85	0.24	.07	0.53	0.53						
1...	16.5	14.3	1.15	0.20	.20	0.44	0.39	1.24	1.24	.014	27 20 N.	150 10 E.	2,890 fathoms
2...	18.0	14.4	1.25	0.32	.21	0.56	0.45						
3...	16.5	14.9	1.11	0.29	.16	0.49	0.43						
14...	17.2	18.6	0.92	0.37	.08	0.51	0.23	......	......	....	12 N.	165 E.	MP 43K, 7 cm. below surface; 2,300 fathoms
15...	15.6	15.2	1.03	0.39	.32	0.71	0.39						
16...	14.5	17.6	0.82	0.38	.24	0.68	0.26						
26...	18.2	19.2	0.95	0.36	.51	0.17	0.70	0.27	1.25	.0057	19 23 N.	....	MP 26A-3
27...	17.1	17.0	1.00	0.29	.52	0.23	1.03						
28...	15.0	14.5	1.04	0.27	.36	0.18	1.97						
4...	15.1	18.5	0.82	0.30	.25	0.22	0.67	0.27	0.77	.0060	52 47 N.	150 05 W.	Gilbert; seamount
5...	14.8	20.0	0.74	0.31	.31	0.17	0.50						
6...	14.5	19.7	0.74	0.34	.37	0.25	0.51						
17...	13.0	19.4	0.67	0.58	.23	0.46	0.31	0.67	0.59	.0018	56 10 N.	145 15 W.	GA-3
18...	12.9	22.5	0.57	0.42	.19	0.47	0.37						
19...	13.3	18.7	0.71	0.35	.35	0.27	0.93						
23...	19.9	22.4	0.89	0.34	.32	0.21	0.85	0.39	0.74	.0038	25 15 N.	119 40 W.	Henderson; seamount
24...	20.1	22.7	0.89	0.35	.37	0.23	0.89						
25...	20.3	18.8	1.08	0.22	.27	0.22	0.67						
7...	12.9	21.4	0.60	0.60	.61	0.42	0.54	0.39	0.81	.0056	17 04 N.	177 15 W.	Cape Johnson guyot
8...	12.6	22.6	0.56	0.65	.64	0.52	0.37						
9...	14.7	19.1	0.77	0.48	.38	0.48	0.72						
20...	6.18	23.8	0.26	0.61	.012	0.89	0.24	1.70	0.27	.0021	27 20 N.	116 10 W.	60 miles SW. Cedros Island; 2,200 fathoms
21...	6.28	19.8	0.33	0.56	.014	0.78	0.39						
22...	8.24	23.6	0.35	0.67	.029	0.80	0.51						
29...	15.8	24.2	0.65	0.66	.40	0.51	0.42	0.29	1.18	.0082	12 N.	165 E.	Sylvania seamount; MP 43
30...	15.9	23.2	0.64	0.56	.71	0.44	0.46						
31...	15.1	23.5	0.64	0.62	.71	0.47	0.36						
32...	9.86	21.0	0.47	1.15	.090	1.81	0.26	1.17	0.31	0.0038	12 42 S.	134 10 E.	Challenger, sample 160
33...	8.79	18.7	0.47	1.05	.069	1.55	0.44						
34...	9.37	20.1	0.47	0.96	0.066	1.58	0.33						

TABLE 3

METHODS OF SPECTROPHOTOMETRIC ASSAY

Element	Method	Modifications	Reference
Fe......	Formation of alpha-alpha dipyridyl complex	....	Snell and Snell, 1949, p. 318
Ni......	Formation of dimethyl glyoxime complex	....	Sandell, 1950, p. 473
Mn.....	Persulfate oxidation to permanganate	....	Nydahl, 1949
Al......	Formation of lake with aluminon	....	Sandell, 1950, p. 147
Cu.....	Formation of diethyldithiocarbamate complex	....	Sandell, 1950, p. 308
Ti......	Formation of complex after addition of hydrogen peroxide	....	Sandell, 1950, p. 572
Zr......	Formation of lake with sodium alizarinate	Initial scavenging with cupferron in 10 per cent HCl solution to remove Mn interference, followed by an ammonium hydroxide precipitation to remove Cu, which interferes by forming a yellow color with thioglycolic acid	Sandell, 1950, p. 641
P.......	Formation of molybdenum blue complex	....	Snell and Snell, 1949, p. 639
Co.....	Formation of nitroso R complex after separation on an alumina column	Microadaptation of a micra-technique	Dean, 1952

will be plated out only when the electrode is positive with respect to the ocean water. Similarly, iron would be deposited during the cycle when the electrode is negative. If the electrodes are charged positively and negatively for nearly equal time intervals, the iron and manganese should accumulate in similar amounts. The tidal energy offers an explanation for the thermodynamics of nodule formation, and the similar iron and manganese contents now appear reasonable.

Further, the deviations from unity of the iron-manganese ratio in table 2 are amenable to a number of alternative explanations. The nodules are representative of eleven varied locations in the eastern Pacific area and are subject to the different oceanographic variables of these regions during their formative period. Any bottom-water mass movement superimposed upon a tidal motion might give rise to a preferential accumulation of one of the colloidal species. The relative values of the size and charge of the manganese and iron sols may be determined partly by the chemical and physical characteristics of the water masses overlying the ocean bed, such as pH, salinity, turbulence, etc. Again, a part of the iron and manganese (in colloidal

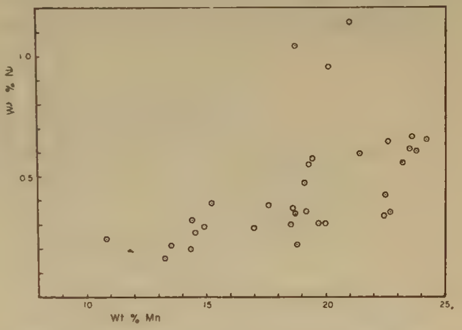

Fig. 1.—The manganese-nickel relationship for eleven manganese nodules.

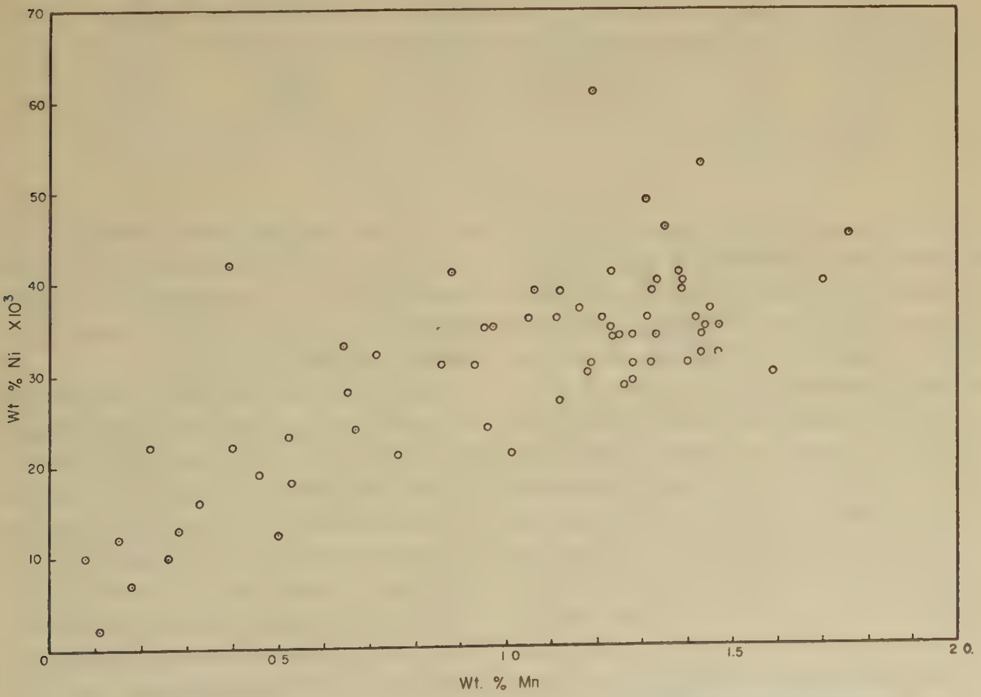

Fig. 2.—The manganese-nickel relationship for a typical eastern Pacific pelagic clay

form) may be of terrestrial or biological origin and reflect more generalized water-mass movements.

In figure 1 the weight per cent of manganese is plotted against the weight per cent of nickel for the eleven Pacific nodules. A linear relationship results, indicating that the nickel has been scavenged by the manganese and that nickel in sea water exists as a cation. Rotschi (1952) has analyzed some eastern Pacific pelagic clays for manganese and nickel by spectrophotometric methods, and his results are plotted in figure 2 for a typical ferruginous clay. It is evident that the nickel-manganese parallelism is similar in nodules and red clays of this type. In table 4 the manganese-nickel ratio of all the Pacific ferruginous pelagic clays analyzed are given with standard deviations. The manganese-nickel ratio is seen to vary between 32 and 53 (except for cores 69 and 70, which will be discussed later), whereas for the nodules this ratio has an average value of 48. Thus it appears that the manganese and nickel in red clays and nodules had a similar origin.

TABLE 4

THE MANGANESE-NICKEL RATIOS OF SOME EASTERN PACIFIC PELAGIC SEDIMENTS

Core	Mn/Ni	σ	Latitude	Longitude	Depth of Water Overlying Core (Meters)	Core Length (Cm.)
69	78	17	13° 25′ S	149° 30′ W.	4,625	6 – 568.5
70	74	10	11 15 S.	150 30 W.	4,920	2 – 381.5
72	46	10	7 38 S.	152 53 W.	4,990	0 –1,457
72B	51	13	7 38 S.	152 53 W.	4,990	1 – 54
77	32	10	2 30 N.	148 40 W.	5,358	1.5–1,380
77B	53	37	2 30 N.	148 40 W.	5,358	0 – 35
83	48	7	8 40 N.	169 28 W.	5,440	2 – 281.5
83B	38	10	8 40 N.	169 28 W.	5,440	0 – 25
85	42	20	5 34 N.	172 12 W.	5,590	5 –1,041.5
85B	41	5	5 34 N.	172 12 W.	5,590	0 – 50
86B	39	21	4 02 N.	172 19 W.	5,500	0 – 40
87B	40	8	2 23 N.	173 50 W.	5,560	0 – 45
Nodules	48	17	....	....	....	....

Pettersson and Rotschi (1952) have proposed that the nickel in ferruginous pelagic clays is derived from meteoritic dust, which constantly showers the earth from outer space. Hence the relative abundance of nickel to other metals in meteorites should be reflected in the manganese nodules (table 1). However, although the range of nickel in the nodules is about double the range of cobalt, there is more than ten times as much nickel as cobalt in gross meteoritic matter. Copper, which is nearly thirty times less abundant in meteorites, is found in manganese nodules in concentrations similar to those of nickel.

Moreover, the meteoritic hypothesis can offer little in explaining the parallelism between the manganese and the nickel, both in red clays and in nodules. It seems reasonable, then, to discard any major contribution of meteoritic dust to sediment formation but to realize that undetermined proportions of elements in both sea water and the sediments may have had as an ultimate source material extra-terrestrial matter.

Figures 3, 4, and 5 depict the linear relationships of the iron content with the titanium, zirconium, and cobalt contents of the nodules. The observation that the first two metals, both transition elements, appear as anions in marine waters is not inconsistent with the known aqueous chemistry of their highest stable oxidation states. On the other hand, the parallelism between cobalt and iron, indicative of an anionic cobalt, appears contrary to the fact that nickel and co-

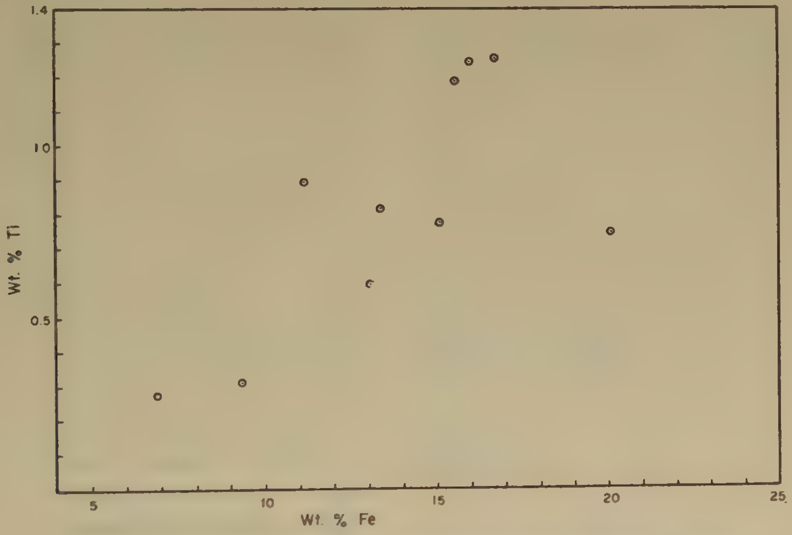

FIG. 3.—The iron-titanium relationship for eleven manganese nodules

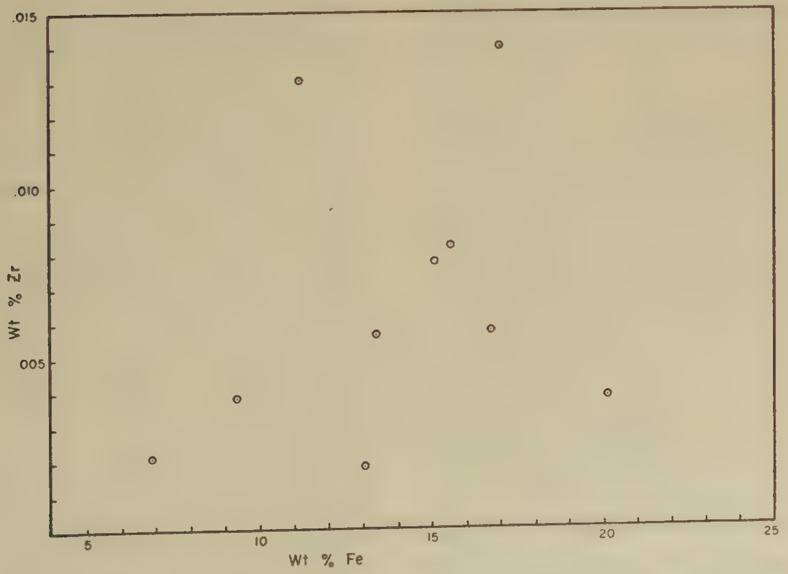

FIG. 4.—The iron-zirconium relationship for eleven manganese nodules

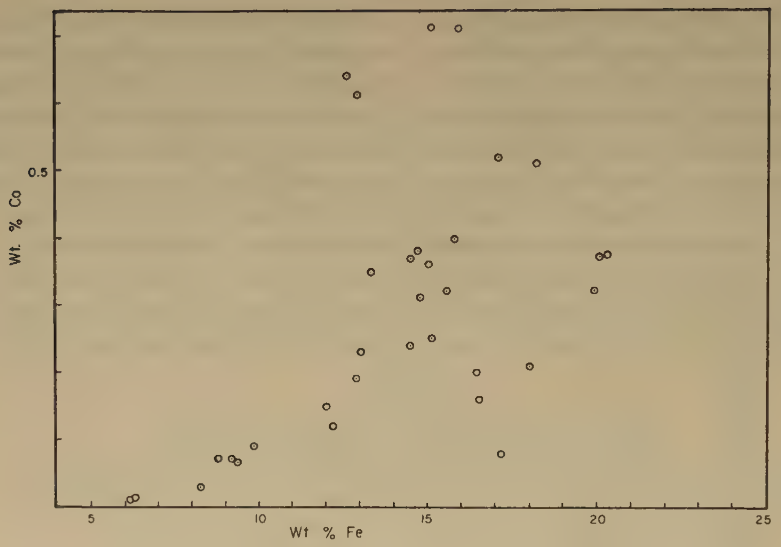

FIG. 5.—The iron-cobalt relationship for eleven manganese nodules

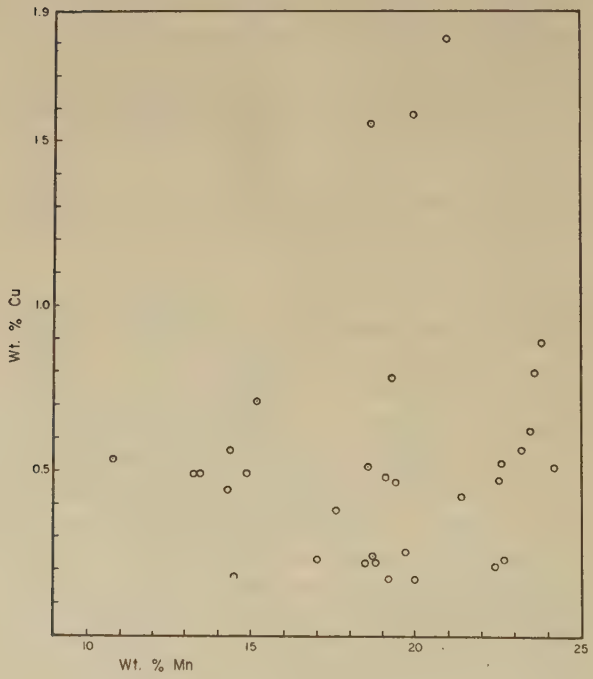

FIG. 6.—The manganese-copper relationship for eleven manganese nodules

balt have similar ionic radii for the doubly charged cations and have generally like geochemical paths in nature. This apparent anomaly will be discussed in the following section.

Copper (fig. 6) appears to follow manganese, while aluminum and phosphorus apparently are independent of either the iron or the manganese contents (table 2). The latter two elements may enter the nodules through colloidal clay particles, iron phosphate sols, etc.

Radium, whose chemistry is similar to that of barium, exists as a cation in aqueous solution and is found in relatively large amounts in manganese nodules. Pettersson (1943) has pointed out a parallel relationship between the manganese and radium contents of the nodules. The radium is scavenged from sea water, while its radioactive parent, ionium, an isotope of thorium, is not or only to a slight extent. This hypothesis is supported by the amount of activity of the radium with reference to the position within the nodule.

In conclusion, for a given amount of manganese or iron of colloidal origin the amount of a scavenged element should be approximately constant over the time interval in which the oceanographic variables have remained unchanged. The striking nickel and manganese relationships of the widely separated red clays and manganese nodules suggest a certain constancy of conditions over the eastern Pacific Ocean. This is further emphasized in the constant manganese-nickel ratios of the vertical profiles of the Swedish cores.

The lattice structures of the manganese nodules are dissimilar to any known iron or manganese mineral and show only broad diffuse bands representative of hydrous oxides. The only sharp band is that due to fine-grained quartz (L. Burkhardt, personal communication). These observations fit into the general pattern of the electrochemical process. The colloidal charge of the sol is discharged at the electrode after being attracted to it. The water of hydration is incorporated into the accretion along with the adsorbed ions.

Revelle (1944, p. 98) has pointed out the widespread occurrence of fine-grained quartz in the pelagic sediments examined from the Carnegie Expedition. Such particles, if they carry an electric charge, could readily be incorporated into the matrix along with any colloidal clay particles. However, this quartz may be authigenic. A mass analysis of the oxygen isotopes of this quartz by the methods outlined by Silverman (1952) would readily distinguish between the authigenic and the terrestrial origins of this material.

The usual location of manganese nodules occurs in regions of low sedimentation rates, such as topographical highs or seamounts. Manganese nodule formation occurs in areas where it would not be masked by biological contributions or detrital or clay constituents falling to the ocean bottom.

If the above considerations are valid, the general factors entering into sedimentation come into perspective. Of prime importance is the distinction between the immediate sources of the sediment and the mechanism of sedimentation. Energy from three main sources, already noted, enters the ocean system to bring material to the ocean floor. The effect of gravitation in drawing down particles with a specific gravity greater than that of the marine waters is obvious. The electrical potentials developed by water-mass movements may have more far-reaching implications than manganese nodule formation suggests.

The latitudinal zonation of the iron-manganese ratio in the Atlantic Ocean pelagic clays has already been observed by Hutchinson (1947). A more pronounced dependence of this ratio upon latitude in the Pacific Ocean emerges from the data of the Carnegie (Revelle, 1944) and of the Swedish Deep Sea Expedition (Rotschi, 1952), as table 5 illustrates. This effect may reflect differences in the magnitudes of the forces causing sedimentation or in the immediate source materials. In the former case, electrochemical forces can cause a preferential settling of either of the two elements. The effect of benthic filter feeders on compacting suspended materials of the water overlying the sediment is probably trivial when compared to gravitational and electrical effects.

TABLE 5

THE IRON-MANGANESE RATIOS OF PACIFIC PELAGIC SEDIMENTS

Latitude	Longitude	Fe/Mn	Reference
40° 37′ N.	132° 23′ W.	6.2	Carnegie 62
33 49 N.	126 20 W.	14.9	Carnegie 64
33 27 N.	145 30 W.	17.8	Carnegie 73
32 42 N.	160 44 W.	26.0	Carnegie 72
31 51 N.	140 50 W.	14.4	Carnegie 74
31 58 N.	128 48 W.	10.7	Carnegie 65
29 21 N.	132 30 W.	10.0	Carnegie 66
26 13 N.	142 02 W.	14.0	Carnegie 69
24 02 N.	145 53 W.	14.9	Carnegie 70
8 40 N.	169 28 W.	4.4	Swedish 83
2 30 N.	148 40 W.	5.0	Swedish 77
7 38 S.	152 53 W.	2.2	Swedish 72B
7 38 S.	152 53 W.	3.0	Swedish 72
11 15 S.	150 30 W.	3.2	Swedish 70
13 25 S.	149 30 W.	3.3	Swedish 69

The sources of the sediment fall into five broad categories. Biological remains, including the hard, inorganic material, such as siliceous or calcareous shells, as well as the organic matter, form the *biogenous* part of a sediment. The *lithogenous* contribution arises from land erosion, submarine volcanoes, or underwater weathering where the solid phase undergoes no change during its stay in the water. The *hydrogenous* part of the solid phases of nonbiological marine origin results from the formation of solid matter in the hydrosphere, such as the precipitation of iron or manganese hydroxides or from chemical solubility products being exceeded, e.g., the formation of calcium carbonate. The *cosmogenous* part of a sediment is derived from the rain of extra-terrestrial particles upon the oceans. A final building material for marine deposits is postulated as being produced in the atmosphere. The formation of beryllium or boron oxides, for example, by the cosmic-ray spallation of nitrogen would result in an *atmogenous* portion of a sediment.

Two general types of sediment-building material, partially independent of their original source, enter this general picture. First, there is the noncolloidal particulate matter which is acted upon mainly by gravitational forces. Second, the colloids, which include the scavengers, of both organic and inorganic origin, are influenced by both gravitational and electrical forces.

Yet certain deductions can be drawn from the above classification. Where the waters of an ocean area are highly productive and where bottom currents are small, the typical pelagic oozes are expected. Where bottom currents are small in nonproductive areas, pelagic clays would predominate. Finally, in areas of relatively high bottom currents, the formation of manganese coatings or nodules may be prevalent, as around guyots and topographical highs. The effect of oceanic currents in the transport and segregation of particles on a size basis must be considered in a genetic analysis of a given sediment. Inasmuch as oceanographic conditions have undoubtedly changed about any particular site on the ocean floor during geological time and since sediments are subject to many disturbing elements, once they are laid down, the complete elucidation of the past history of a deposit is obviously a formidable task.

The usefulness of the above classification presents itself in the problem of titanium dating, as outlined by Arrhenius, Kjellberg, and Libby (1951). The basis of this method of determining the rate of sedimentation rests with the thesis that there is a constant average rain of minerogenous material over the ocean bottom. The authors state: "As a measure of the minerogenous component the concentration of titanium recalculated for salt free sediment has been used." It is further emphasized that a constant titanium content of the minerogenous component and constant rate of sedimentation must be established in all cases where this dating technique is to be used. (The criteria for these conditions are further elaborated by Arrhenius [1952].)

However, three immediate sources of titanium are apparent: The minerogenous (i.e., hydrogenous and terrigenous) are in no need of further amplification; the biogenous titanium becomes evident as a constituent of diatoms (Griel and Robinson, 1952). The titanium content of a diatom may result from the uptake of colloidal iron by the plant cell (Goldberg, 1952) but, nevertheless, should be considered of biological origin with respect to sediment formation. Hence a restatement of the criteria for titanium dating becomes manifest. The forces tending to cause precipitation must be constant over the time of sedimentation. Further, the immediate source material of the sediment must, in effect, remain unchanged in type as well as in amount with respect to the three main classifications.

The utility of the genetic classification of sediments is revealed in considerations of elemental ratios in ascertaining a semiquantitative account of the building blocks. The association of scavenged elements and the scavengers is indicative of the hydrogenous contribution to a sediment. As an example, the manganese-nickel ratios of the eastern Pacific ferruginous clays of Rotschi and the manganese nodules fall within the same range except for cores 69 and 70 (table 4). Both these latter deposits contain high amounts of volcanic glass, palagonite, and phillipsite, and their high values of manganese to nickel reflect the chemical composition of these rocks, minerals, and their progenitors. Hence it is deduced that approximately one-third of the manganese in these cores is not of the hydrogenous type.

Specific associations of elements in the hard parts of organisms can be indicative of the biogenous portion of a sediment, such as the difference of the calcium-strontium ratio in calcareous remains and in inorganically precipitated calcium carbonate.

Elements that form minerals which are resistant to chemical and mechanical weathering present themselves as traces of the minerogenous portion of a sediment. Quartz, zircon, and beryl appear promising. In cases where an element is in the hydrogenous, biogenous, and lithogenous fractions, advantage must be taken of the stability of the lithogenous species to separate them from the sediment for analyses. Dilute acid treatment of a sediment, followed by fractional centrifugation, often accomplishes this end. The quartz content of a sediment would be connotative of the lithogenous matter, if it is not authigenic.

The titanium-zirconium ratio is also indicative of the past history of the sedimentary matter. The ratio in manganese nodules, which are presumed to be almost entirely hydrogenous, averages 150, whereas in igneous rocks the ratio of 20 is reported (Rankama and Sahama, 1950). Thus values of titanium to zircon of the order of magnitude of the igneous-rock ratio suggest the presence of lithogenous matter in the deposit.

TRACE ELEMENTS IN MARINE WATERS

The ability of iron and manganese oxides to collect and maintain ions from sea water leads to the concept of the *marine partition coefficient*, which may be defined as the ratio of an element in the solid phases to that in a given volume of solution. Thus, for iron, with a maximum ionic concentration of 0.5 μgm/liter (excluding, of course, any organic complexes that may be present) and a particulate concentration range of 1–100 μgm/liter, the partition coefficient is of the order of 2–200. With respect to manganese, from the data previously cited, the coefficient would approximate 0.7.

TABLE 6

Partition Coefficients of Some Elements in Marine Waters

Element	Marine Partition Coefficient
Fe	2 –200
Mn	0.7
Cu	0.01– 0.1
Ni	0.04– 0.4
Co	0.02– 2
Ti	0.05– 5

Ionic copper amounts to around 4 μgm/liter (Chow and Thompson, 1952). The copper adsorbed to manganese, which contains about one-thirtieth of its weight in copper, would be 0.03–0.30 μgm/liter. Hence the partition coefficient for copper would range from 0.01 to 0.1. The partition coefficients calculated for some other elements are shown in table 6.

The marine partition coefficients represent an approach to equilibrium in nature. If the scavenger undergoes a change of environment, resulting changes in the concentration of the collected ions might be expected. Such a situation may arise when hydrogenous iron or manganese oxides become a part of a sediment and are in contact with the interstitial water. The quantities of this water are constantly changing with respect to the dissolved ions by chemical, physical, and biological processes within the deposit.

The foregoing picture of elemental distributions between two phases in sea water leads directly to more dynamic considerations. The presence of these trace elements in a particulate form places a limit on the time during which they may be associated with a particular water mass, for the iron and manganese sols are continuously being removed by sedimentation or biological processes (as will be illustrated in the next section). In the case of nickel, for example, the solubility product of its oxide does not limit its concentration in marine waters, for it is a simple experiment to dissolve a crystal of nickelous chloride in a sea-water solution; but its ionic content is maintained at a level determined by manganese scavenging. Table 7 shows the concentration of some scavenged ions in sea water and the potential concentration of these ions if they were limited by the solubility product of one of their compounds.

Of further interest is the determination of the charge of certain of the trace elements in sea water by the scavenger with which they are associated. Already we have observed that nickel and copper are positively charged, whereas titanium, zirconium, and cobalt are negatively charged. It would now be of further interest to consider this problem from a chemical point of view based upon modern structural theory.

The charge on a metallic ion in sea water depends upon the charges on the complexing groups or ligands which coordinate with it (see Bjerrum, 1950). According to the modern views of chemical structure based on quantum-mechanical considerations, metal ions become solvated as they go into solution. The solvent molecules can be replaced by ligands, and equilibrium constants can be determined to describe such processes. If equilibrium is established, all energetically and sterically possible ionic complexes will exist in amounts determined by their equilibrium constants.

Such a calculation can be made for copper and chloride according to the published data of Bjerrum (1946). Concentrations are utilized instead of activities. This approximation will give a general idea of the distribution of the ionic species of copper. The (Cl^-) is placed equal to 0.7 M, and a total copper content of 10×10^{-8} M is assumed:

$$k_1 = \frac{(CuCl^+)}{(Cu^{++})(Cl^-)} = 10^{-0.2},$$

$$k_2 = \frac{(CuCl_2)}{(CuCl^+)(Cl^-)} = 10^{-0.7},$$

$$k_3 = \frac{(CuCl_3^-)}{(CuCl_2)(Cl^-)} = 10^{-1.5},$$

$$k_4 = \frac{(CuCl_4^{--})}{(CuCl_3^-)(Cl^-)} = 10^{-2.2},$$

$$Cu^{++} + CuCl^+ + CuCl_2 + CuCl_3^- + CuCl_4^{--} = 10 \times 10^{-8}\ \mathrm{M}.$$

Solving the five simultaneous equations in five unknowns, the following concentrations are found: Cu^{++}, 6.5×10^{-8}; $CuCl^+$, 2.9×10^{-8}; $CuCl_2$, 0.4×10^{-8}; $CuCl_3^-$, 0.9×10^{-10}; and $CuCl_4^{--}$, 0.6×10^{-13}. Thus, over 99 per cent of the copper in sea water is in a neutral or positively charged form, assuming that chloride is the only ligand in equilibrium with the solvated cupric ion.

Data are not available for computing the distribution of nickel and cobalt among various ionic species with the ligand chloride. Hence the observation that the majority of the cobalt is in a negatively charged form, whereas the nickel is apparently positively charged, has not been verified.

TABLE 7

THE SOLUBILITIES OF SOME CATIONS IN MARINE WATERS

Element	Observed Concentration in Sea Water (Moles/Liter)	Calculated Maximum Concentration in Sea Water Assuming Solubility Is Limited by Hydroxide
Ni^{++}...	1×10^{-8}	6.5×10^{-6}
Co^{++}...	2×10^{-9}	2.5×10^{-4}
Cd^{++}...	5×10^{-9}	2×10^{-2}
Pb^{++}...	1×10^{-8}	4.7×10^{-7} (sulfate limiting)
Tl^+....	$< 5 \times 10^{-11}$	4×10^{-4} (chloride limiting)

These concepts will come into more prominence as more data are obtained, both on scavenging and on the distribution of ligands among cations. It is apparent, nonetheless, that both negative and positive sols will scavenge any given metal in solution, with the majority of the element in question going to the sol carrying an opposite charge.

Such ideas are useful in the interpretation of the sedimentation of the radioactive elements of marine waters. It has previously been assumed that ionium, an isotope of thorium, is scavenged by iron. However, the aqueous chemistry of thorium reveals that it exists in solution mainly as a positively charged ion; it would therefore be expected to follow manganese.

SCAVENGERS AND THE BIOSPHERE

Chemical studies on the ashes of marine plants and animals have revealed the existence of large amounts of trace elements, such as copper, zinc, cobalt, titanium, vanadium, etc. That some elements are concentrated in the marine biosphere that have not as yet been detected in sea water has made these observations all the more striking. It is therefore inviting to explore the possible mechanisms for the concentration of these minor constituents.

TABLE 8

THE IRON-TITANIUM AND MANGANESE-NICKEL RATIOS IN THE ASHES OF SOME SEAWEEDS

SPECIES OF PLANT	OVEN-DRIED, JANUARY 12, 1949		OVEN-DRIED, MAY 26, 1949		OVEN-DRIED, JUNE 27, 1950		WET, JUNE 27, 1950	
	Fe/Ti	Mn/Ni	Fe/Ti	Mn/Ni	Fe/Ti	Mn/Ni	Fe/Ti	Mn/Ni
Pelvetia canaliculata	18	37	15	6	34	11	34	11
Ascophyllum nodosum	19	33	11	6	41	10	41	10
Fucus serratus	80	500	19	48	46	27	44	26
F. spiralus	....	....	24	17	11	13	11	13
F. vesiculosus	....	....	8	31	27	17	18	18

Two general possibilities for the uptake process merit consideration. The first would involve the direct transfer of an ionic species from the hydrosphere to the organism. Spooner (1949) has demonstrated that radioactive strontium is extracted from sea water by the brown seaweeds by a factor of fourteen to forty fold over the marine environment. Red and green algae took up this element to a much smaller extent. Radioactive yttrium was concentrated by red algae and by green algae. In both cases of elemental concentration the author postulated a direct uptake of the element by either ion exchange or surface adsorption.

Ionic vanadium is specifically adsorbed by the mucus of tunicates (Goldberg, McBlair, and Taylor, 1950), while the mucus of some marine lamellibranchs examined by Goldberg and Rao (unpublished data) has the ability to take up large amounts of calcium.

Of extreme interest is the method by which sponges and siliceous algae obtain the silicon for test formation. Although no silicon-carbon or silicon-oxygen compound in nature has been definitely established, it is highly reasonable to believe some type of organic molecules formed from ionic silicates exists to provide transfer of this element from the marine environment to the test via the soft parts of the organism.

A second form of accumulation may apply to the uptake of scavengers along with the scavenged elements. Such would be the case with respect to the high titanium content of marine diatoms, as found by Griel and Robinson (1952), which has already been cited. Black and Mitchell (1952) have made a spectroscopic survey of the abundance of trace elements in common brown algae. These investigators studied the ashes of different seaweed species collected at three different times in 1949 and 1950. The ratios of manganese to nickel and of iron to titanium are reproduced in table 8. The values are similar to the ratios found in the manganese nodules and pelagic clays of the Pacific Ocean, although the specimens were obtained from Atlantic Ocean waters. At this point it should be emphasized that the spectroscopic data are precise only to factors of 2 or 3 and that general trends are sought. The one exception to this parallelism occurs in *Fucus serratus*, collected on January 12, 1952, where both ratios appear abnormally high.

TABLE 9

THE IRON-TITANIUM AND MANGANESE-NICKEL RATIOS OF SOME MARINE ORGANISMS

Animal	Fe/Ti	Mn/Ni	Reference
Ascidia: *Ciona intestinalis*	147	7.5	Noddack and Noddack (1940)
Sponge: *Halichondria*	297	2.7	
Acaleptes: *Cyanea capillata*	25	2.0	
Actinias: *Metridium dianthus*	85	2.4	
Holothurias: *Stichopus tremulus* (without intestines)	103	1.0	
Asteroids: *Asterias rubens* (without intestines)	180	7.9	
Sponges: *Dysidea crawshayi* (1946)	181	0.05	Bowen and Sutton (1951)
Dysidea crawshayi (1947)	225	2.3	
Dysidea etheria (1948)	> 30	12	
Dysidea etheria (1946)	184	7.7	
Condrilla nocula (1946)	>100	2.3	
Condrilla nocula (1946)	> 51	0.4	

Marine invertebrates that filter particles in suspension in sea water and/or pass marine detrital material through their internal parts should exhibit in their ultimate constitution the results of the uptake of undifferentiated particulate matter. Scavenged elements or the scavengers thus may enter the organisms directly, through phytoplankton, fecal material, or biological remains. If elements are concentrated initially by organisms through their ingestion of inanimate scavengers, fractionation processes with regard to the scavenged elements and the scavengers undoubtedly take place, depending upon the necessity or ease of incorporation of a given element into the organism.

A general analysis of trace-mineral constituents of marine organisms is hampered by the lack of adequate analyses of more than one or several elements for a given species. The few sets of data that are set forth herewith were selected because of the refined chemical techniques and the combinations of the elements analyzed. Noddack and Noddack (1939) used highly refined spectroscopic techniques for analyzing some marine organisms from one of the Swedish fjords from which the manganese-nickel and iron-titanium ratios are listed in table 9. Also tabulated are similar measurements on marine sponges made spectroscopically by Bowen and Sutton (1951). The manganese to nickel ratio is low compared to the value in red clays and manganese nodules. Such a condition may arise when the nickel, coming into contact with the lower pH of the internal parts of an organism, is released in an ionic form, whereas the difficultly soluble manganese oxides are rejected. Such a mechanism of concentration of nickel relative to manganese may have occurred in the plankton whose bodies or parts thereof are taken in as food. Bowen and Sutton attribute the extremely high nickel content of *Dysidea crawshayi* of 1946 to a microflora which had the ability to concentrate nickel to a remarkable degree.

The iron-titanium ratios reported by both observers reflect closely the results quoted by Koczy (1950) on various sediments from the Meteor Expedition in the Atlantic. Yet they are somewhat higher than the values reported by Black and Mitchell for the algae, indicating a possible fractionation of iron over titanium in the organism. Such a result is not unexpected, since iron is utilized in metabolic processes of the organisms and may be separable from any adsorbed titanium.

CONCLUSION

The preceding treatment has considered but two of the potential scavengers of sea water and their effect upon the path of chemical elements in the oceanic system. The organic particulate matter arising from the death and metabolic waste products of organisms has the ability to incorporate metallic ions from the marine environment by adsorption as well as by such possible chemical reactions as metal-ion replacements in porphyrins. The adsorptive ability of clays has initiated many studies in the past. The scavenging effects of aluminum hydroxide, silicon oxides, etc., which exist colloidally in sea water, have likewise fallen outside the range of this paper.

Emphasis has been placed upon the oceans as a multiphased chemical system in which the distribution of some ionic species is influenced by their adsorbability by particulate iron and manganese oxides. Thus the "characteristic ratio" of adsorbed ions to the scavenger is useful as a tracer of elemental fractionation in the oceans.

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THE EFFECT OF WINDS AND BODILY TIDES ON THE ANNUAL VARIATION IN THE LENGTH OF DAY

by

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THE EFFECT OF WINDS AND BODILY TIDES ON THE ANNUAL VARIATION IN THE LENGTH OF DAY

Yale Mintz and Walter Munk†*

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Summary

The effect of winds is to vary the length of day by 0·7 milliseconds between February and August. The bodily tides result largely in a semi-annual variation of 0·4 ms. The combined effect of winds and tides is not far out of line with astronomical measurements since 1950. The fluid core of the Earth hardly participates in these variations in angular velocity and there is a half-year slippage of 23 metres between core and mantle at the equator. Eventually the astronomical measurements may provide a basis for determining the Love number *h*.

1. *Introduction.*—With the development of modern quartz crystal clocks it has become possible to measure slight annual variations in the length of day. The existence of an annual variation was discovered by various authors in 1934–1937, and since then there have been numerous reports by Stoyko, Scheibe and Adelsberger, Finch, Uhink, and others.

The first attempt to account for these variations was made by Van Den Dungen, Cox and Van Mieghem‡ 15 years after their discovery. They considered the effect of seasonal shifts in air mass on the moment of inertia of the Earth. This seasonal shift has been known for some time to account for most of the observed annual wobble of the Earth's axis of rotation (as deduced from measurements of latitude§) and it seemed quite natural to look for a similar effect here. Van Den Dungen's calculations were for the northern hemisphere only and they yielded 20 per cent of the observed effect. Munk and Miller|| extended the calculation to include the southern hemisphere (which largely compensates for the shift in the northern hemisphere) and allowed for the role played by temperature in the correction from sea-level pressure changes to local pressure changes.¶ This gave one-tenth of Van Den Dungen's result. The effect of vegetation and snow was also found to be small. The most troublesome part of the inertia calculations concerns the effect of seasonal shifts in ocean water. By an indirect method Munk and Miller estimated this to be of the order of 10 per cent of the observed effect, but there is some doubt now concerning the validity of their calculation. It is interesting that a similar numerical value

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† Contribution from the Scripps Institution of Oceanography, New Series No. 693, supported under a contract with the Office of Naval Research.

‡ F. H. Van Den Dungen, J. F. Cox and J. Van Mieghem, " Sur les Fluctuations de Periode Annuelle de la Rotation de la Terre ", *Bull. Acad. r. de Belg. Sciences*, **35**, 642–655, 1949.

§ Harold Jeffreys, *The Earth*, Chapter 7, London, 1952.

|| W. H. Munk and R. L. Miller, " Variations in the Earth's Angular Velocity Resulting from Fluctuations in Atmospheric and Oceanic Circulation ", *Tellus*, **2**, 93–101, 1950.

¶ This was discussed in " Letters to the Editor ", *Tellus*, **2**, 319–321, 1950.

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was obtained by Lawford and Veley* in a calculation based on tide gauge records. The difficulty with the latter method is that most of the annual variation in sea level is due to heating and cooling of water, and not to changes in the distribution of mass of sea water as implicitly assumed by the authors.

Altogether the annual changes in the moment of inertia of the atmosphere and hydrosphere appear to be too small (but not very much too small) to account for the observed variations in the Earth's rotation. On the other hand, the variation in the angular momentum of the atmosphere has a more important effect. The largest portion is contained in the "jet stream" and surrounding westerlies which have been properly recorded only in the last decade. Munk and Miller† computed the resulting January to July change in the length of day and obtained 1·8 ms. The early astronomical measurements, though badly scattered, were not inconsistent with this value.

A re-computation by Mintz and Munk‡ incorporated new data for the southern hemisphere, and extended the calculation in the northern hemisphere to include a compilation by Mintz and Dean of the zonal winds at *all* longitudes. Munk and Miller had used only the published sections along 100° E. and 80° W. It turned out that the variations at 100° E. and 80° W. are substantially larger than at all other longitudes, and this led to a reduction in the computed January to July change from 1·8 ms to 0·5–0·8 ms. On the basis of the new calculations it was concluded that only one-third to one-half of the observed variation could be attributed to winds.

This paper gives the result of a third calculation. The principal new feature is that the calculations were extended from two to four seasons, and to monthly values at two elevations in the northern hemisphere. This makes it possible to sketch the annual curve. We have also allowed for the fluidity of the Earth's core. It does not seem likely to us that the present estimate can be appreciably improved until extensive new observations are made of upper air winds over the southern oceans, and this may not happen for some time to come.

The computed change for January minus July is now 0·7 ms, compared with 0·5 to 0·8 ms in our previous calculation. This in itself would not lead to any change in conclusions. However, the estimate based on astronomical measurements has now been substantially reduced§, and for the years following 1950 it is placed at 0·6 ms, in satisfactory agreement with the computed value. The revision is due partly to an improvement since 1950 in the quartz crystals and control circuits, partly to corrections for periodic errors in the right ascensions of the FK3 catalogue.|| There remains also the possibility of a real reduction in the amplitude of the annual term since 1950, though meteorological observations north of 20° N. do not indicate any significant anomalies in recent years. With the reduction by a factor of three of both the atmospheric and astronomical terms (each revision for its own peculiar reason) the conclusion now seems to be what it was in the first place, namely that the annual change in the length of day is due largely to winds.

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*A. L. Lawford and V. F. C. Veley, "Variations in the Length of Day", *Nature, Lond.*, **167**, 684, 1951.

† W. H. Munk and R. L. Miller, *op. cit.*

‡ Y. Mintz and W. Munk, "The Effect of Winds and Tides on the Length of the Day", *Tellus*, **3**, 117–121, 1951.

§ Humphry M. Smith and R. H. Tucker, "The Annual Fluctuation in the Rate of Rotation of the Earth", *M.N.*, **113**, 251, 1953.

|| We are indebted to the Astronomer Royal for information concerning these developments.

In principle the effect of the wind circulation on the Earth's rotation could be computed by two independent methods: (*a*) from changes in the angular momentum of the atmosphere as a whole, or (*b*) from the momentum transfer (stress) between the atmosphere and Earth. Van Den Dungen *et al.** state that "it is generally accepted that available aerological information concerning the distribution, in space and time, of the zonal component of the atmospheric circulation is not yet complete enough to permit a reliable calculation of the angular momentum of the atmosphere", and that "the annual variation of the momentum transfer between the Earth and the atmosphere offers a better basis . . .". We do not agree. A six-month change by 1 ms in the length of the day corresponds to an average rate of change in angular momentum of $0{\cdot}4 \times 10^{26}$ g cm^2 s^{-2}. But the total westerly torque and the total easterly torque of the atmosphere on the Earth are each of the order of 10×10^{26} g cm^2 s^{-2}. To come within 25 per cent, the surface torques would have to be known to an accuracy of one part in a hundred! The corresponding requirement for the total angular momentum is less than one part in ten (see Table I, p. 571).

2. *The fluid core.*—Let I denote moment of inertia and ω the appropriate average angular velocity, with the subscripts a, m, c referring to atmosphere, and to mantle and core of the Earth. Conservation of angular momentum requires that

$$I_a\omega_a + I_m\omega_m + I_c\omega_c = \text{constant}. \tag{1}$$

In addition, there is electromagnetic coupling† between mantle and core (viscous coupling is negligible), and the resulting couple equals

$$L = k(\omega_m - \omega_c) = I_c \frac{d\omega_c}{dt} \tag{2}$$

Suppose that at time $t=0$, ω_m changes abruptly from zero to one. The appropriate solution is $\omega_c = 1 - e^{-\gamma t}$, with

$$\frac{1}{\gamma} = \frac{I_c}{k} \tag{3}$$

denoting the "time constant" of electromagnetic coupling.

For an annual variation (frequency σ) we set

$$\omega_a = \cos \sigma t,$$

$$\omega_m = r_m \cos(\sigma t - \alpha_m),$$

$$\omega_c = r_c \cos(\sigma t - \alpha_c).$$

Equations (1) to (3) yield

$$r_m = r_c\sqrt{1+\tau^2}, \qquad r_c = -(I_a/I)[1+\tau^2(I_m/I)^2]^{-1/2},$$

$$\alpha_m = \alpha_c - \theta, \qquad \tan\alpha_c = \tau(I_m/I),$$

where $I = I_m + I_c$ is the Earth's moment of inertia and $\tau = \sigma/\gamma = \tan\theta$. Hence $\tau/2\pi$ is the time constant of electromagnetic coupling in years.

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* "Letters to the Editor", *Tellus*, **2**, 319–321, 1950.

† E. C. Bullard, C. Freedman, H. Gellman and J. Nixon, "The Westward Drift of the Earth's Magnetic Field", *Phil. Trans.* A, **243**, 67–92, 1950.

Bullard* estimates $\tau/2\pi \approx 100$ years. Recent estimates† based on a correlation between changes in a decade or two of the length of day and of the westward drift of the Earth's magnetic field would indicate $\tau/2\pi \approx 10$ years.‡ Appreciably smaller values of $\tau/2\pi$ would require unreasonably large values of the electric conductivity in the mantle. Therefore, $\tau \gg 1$, and

$$r_m \approx -I_a/I_m, \qquad r_c \approx r_m/\tau \approx 0,$$

$$\alpha_m \approx -I_c/(I_m\tau) \approx 0, \qquad \alpha_c \approx \frac{\pi}{2} - I/(I_m\tau) \approx \frac{\pi}{2}.$$

To the present approximation we may therefore compute the effect of winds as if the core were absent; or

$$I_a\omega_a + I_m\omega_m = \text{constant}. \tag{4}$$

Since the core accounts for 10 to 12 per cent of the Earth's moment of inertia, the effect of the winds is increased in the ratio $I/(I-I_c)=1{\cdot}1$ compared with what it would be for a solid core.

The half-year slippage between core and mantle at the equator is $\frac{\pi}{2\sigma} a_c \Delta\omega_m \approx 23$ metres, where a_c is the radius of the core. The slippage takes place within a boundary layer§ of thickness $\sqrt{2\nu/\sigma}$, where ν is the kinematic viscosity in the core. The viscosity is only vaguely known. A theoretical estimate by Bullard|| for the molten iron in the core gives 10^{-3} cm^2 s^{-1}; the damping of the 14-monthly variations of latitude indicates 10^5 cm^2 s^{-1} as an upper limit¶; the damping of compressional waves yields an even larger upper limit¶ of 5×10^7 cm^2 s^{-1}. The corresponding widths of the boundary layer are 1 metre, 10 km and 220 km.

3. *The annual variation in the angular momentum of the atmosphere.*—Fig. 1 shows seasonal pole-to-pole plots of the mean zonal wind

$$U = \frac{1}{2\pi}\int_0^{2\pi}\delta\lambda \frac{1}{910}\int_{1010\,\mathrm{mb}}^{100\,\mathrm{mb}} u(\lambda, p)\,\delta p \tag{5}$$

averaged over all longitudes λ and between the surface (1010 mb pressure) and the 100 mb level. The calculation includes, therefore, all but the upper 10 per cent of the mass of the atmosphere.

North of 20° N. latitude u is taken as the relative geostrophic zonal wind computed from circumpolar maps of the normal pressure distribution at sea level, 700 and 500 mb and 10, 13, 16 and 19 km elevations. Between 20° N. and 20° S. the winds are based on circumpolar pilot balloon and radar wind observations. South of 20° S. the winds are again geostrophic, but confined to the longitude sector of Australia and New Zealand. The assumption was made that the average zonal winds in this section of the southern hemisphere are equivalent to the winds averaged over all longitudes. The sources of the data, and composite pole-to-pole meridional cross sections of the zonal wind for January

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* E. C. Bullard, *et al.*, *loc. cit.*

† Walter Munk and Roger Revelle, "On the Geophysical Interpretation of Slight Irregularities in the Rotation of the Earth", *M.N.*, *Geophys. Suppl.*, **6**, 331–347, 1952.

‡ A new evaluation of electric conductivity of the mantle near the core by H. Hughes (unpublished) also yields a 10-year time constant.

§ Horace Lamb, *Hydrodynamics*, p. 622, Cambridge.

|| E. C. Bullard, "The Secular Change in the Earth's Magnetic Field", *M.N.*, *Geophys. Suppl.*, **5**, 248–257 (p. 256), 1948.

¶ Harold Jeffreys, *loc. cit.*, pp. 244–246.

and July, are given in a forthcoming paper.* For April and October the same data sources were used for the winds north of 20° S., but south of 20° S. latitude the winds were taken directly from cross-sections published by Gibbs.†

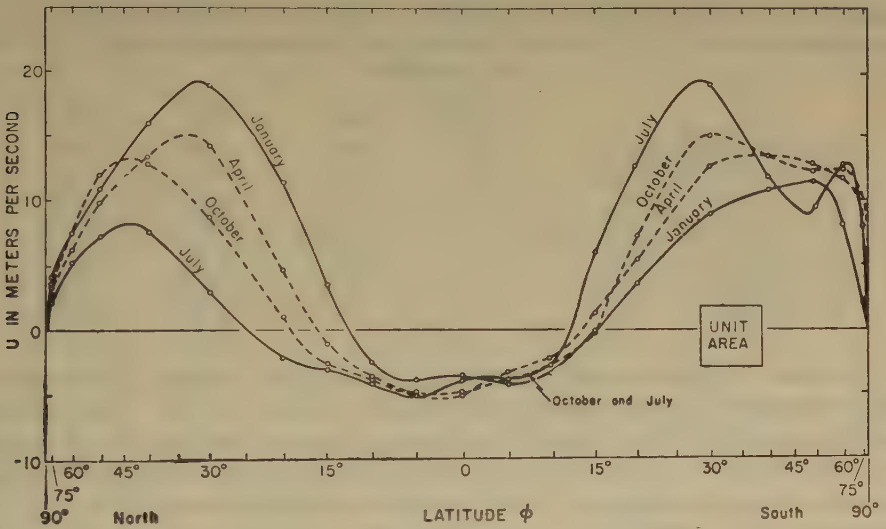

FIG. 1.—*The curves denote the relative westerly zonal winds, averaged over all longitudes and over the lower 90 per cent of the mass of the atmosphere, as a function of* $\int_0^\phi \cos^2\phi\, d\phi$, *where* ϕ *is latitude. For this function the area under each curve is proportional to relative westerly angular momentum; unit area equals* 10^{32} *g cm*^{2} *sec*$^{-1}$. *An increase by this amount corresponds to an increase by* 0·163 *ms in the length of day.*

By graphical integration of the areas under the curves in Fig. 1 the relative westerly angular momentum of the atmosphere is found from the relation

$$(I\omega)_a = \frac{2\pi a^3 p_0}{g} \int_{-\pi/2}^{\pi/2} U \cos^2\phi\, d\phi,$$

where a is the Earth's radius, g gravity and p_0 the mean atmospheric pressure at the surface. The resulting changes by ΔT in the length of day T then follow from equation (4):

$$\Delta T = \frac{\Delta(I\omega)_a}{I_m\omega_m} T.$$

Numerical values are given in Table I.

It is clear that the atmosphere's contribution to the annual changes in the length of day owes its existence to the lack of cancellation between the two hemispheres. The principal difference is the larger momentum in the southern hemisphere during the southern summer, as compared to the northern hemisphere during the northern summer (6·5 versus $3{\cdot}0 \times 10^{32}$ g cm^2 s^{-1}). In a qualitative way this can be traced to the asymmetry in the distribution of land and sea. In the northern hemisphere there is a proportionately larger fraction of land in middle and high latitudes, resulting in warmer middle and high latitude summer temperatures and hence a smaller poleward temperature gradient and weaker upper-level winds.

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* Y. Mintz, "The Observed Zonal Circulation of the Atmosphere", *Bull. Am. Met. Soc.*, in the press.

† W. J. Gibbs, "A Comparison of Hemispheric Circulation with Particular Reference to the Western Pacific", *Quart. Journ. Roy. Met. Soc.*, **79**, 121–136, 1953.

Table I

Relative westerly angular momentum of atmosphere, $(I\omega)_a$, and its variations $\Delta(I\omega)_a$ from the annual mean, in units of 10^{32} g cm^2 sec^{-1}, together with the resulting variations by ΔT ms in the length of day

	Jan.	April	July	Oct.
90° N. to 20° N., $(I\omega)_a$	10·5	8·1	3·0	6·6
20° N. to 20° S., $(I\omega)_a$	−1·0	−2·2	−1·7	−2·8
20° S. to 90° S., $(I\omega)_a$	6·5	9·0	10·5	9·7
90° N. to 90° S., $(I\omega)_a$	16·0	14·9	11·8	13·5
90° N. to 90° S., $\Delta(I\omega)_a$	1·95	0·85	−2·25	−0·55
90° N. to 90° S., ΔT	0·32	0·14	−0·37	−0·09

To obtain a more detailed picture of the seasonal change in atmospheric angular momentum, the angular momentum north of 20° N. was computed *month by month* for the 700 and 500 mb levels, the two levels for which the data are most reliable.* The results, given in Fig. 2, show maximum angular momentum in early February and minimum angular momentum in late July or early August. Generalizing from these two levels, one may assume that the entire angular momentum north of 20° N. has its maximum and minimum at these times of the year. On the basis of these considerations we have extrapolated the four computed values for the total atmosphere (Table I) to the curve drawn in Fig. 2. This represents our best estimate concerning the effect of winds on the length of day.

4. *The constancy of the annual variation in atmospheric momentum.*—It has been pointed out in the introduction that there is some suggestion in the astronomical observations of a reduction in the annual variation since 1950. To examine this possibility we have computed the westerly angular momentum of the atmosphere north of 20° N. at the 700 mb level month by month from 1948 November until 1952 March, and at the 500 mb level, taking five-day means, from 1949 January until 1950 April. When these curves are compared with the corresponding *normal* monthly values at the levels, as derived from U.S. Weather Bureau normal charts, they are found not to differ significantly.

The data for the northern polar cap alone are of course not conclusive and a similar calculation should be made for the equatorial zone and southern hemisphere. This is a major undertaking, as it would involve going back to original data. Even so, there is doubt as to whether the available equatorial and southern observations are sufficiently complete to reveal the possible existence of year-to-year anomalies.

5. *The effect of tides.*—In the shape of the Earth there is a slight additional protuberance, on the average, in the equatorial region at the expense of the polar regions, and a resulting increment in the Earth's moment of inertia over what it would be if the Sun were absent. The essential effects here are *variations* in this increment due to (*a*) variations in the Sun's distance from the Earth, and (*b*) changes in the Sun's declination because of the obliquity of the ecliptic.

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* U.S. Weather Bureau, " Normal Weather Charts for the Northern Hemisphere (sea level, 700 and 500 millibars) ", *Technical Paper* No. 21, Washington, D.C.

The former gives rise to a small annual term; the latter to a semi-annual term with minima in the moment of inertia (and thus the length of day) at summer and winter solstices, and maxima at spring and fall equinoxes (see Fig. 3).

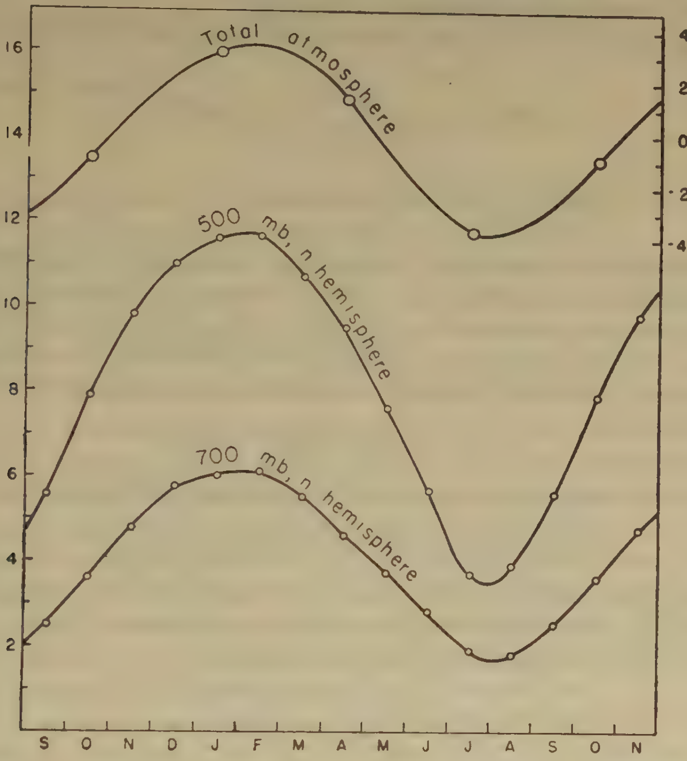

FIG. 2.—*The two lower curves give the relative westerly angular momentum of the polar cap north of* 20° N. *contained between the* 699·5–700·5 *mb and* 499·5–500·5 *mb isobaric surfaces, respectively. The units are in* 10^{29} *g* $cm^2\ s^{-1}$ *per mb and refer to the left scale. The month by month calculated averages are indicated by small circles. The upper curve gives the relative westerly angular momentum of the total atmosphere in units of* 10^{32} *g* $cm^2\ s^{-1}$ *(left scale). The computed seasonal values are shown by the larger circles. The curve has been sketched with the guide of the two lower curves. The scale to the right gives the resulting variation in ms in the length of day.*

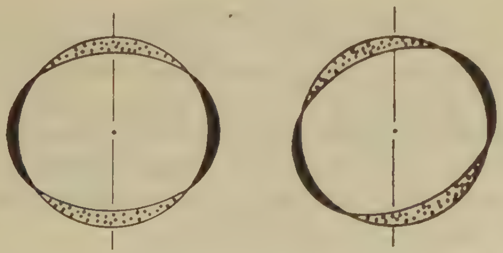

FIG. 3.—*The tidal bulge during equinox (left) and solstice (right).*

Jeffreys* first drew attention to the role of the obliquity before this effect was discovered. Stoyko† referred to it but made a numerical error and used the wrong Love number (k instead of h). We* also used the wrong Love number, and for this and other reasons came out with about three-quarters of the correct value. The effect is quite large, second only to the winds, as will be seen, and a systematic derivation is indicated.

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* H. Jeffreys, " Possible Tidal Effects on Accurate Time-keeping ", *M.N.*, *Geophys. Suppl.*, **2**, 56–58, 1928.

† N. Stoyko, " La Variation de la Vitesse de Rotation de la Terre ", *Bull. Astronomique*, **15**, fasc. 3, 14 pp., 1951.

The long-period species of the solar equilibrium tides is given (*A.M. of T.*, 4·3)† by

$$\left.\begin{aligned} z &= K\tfrac{3}{4}(\tfrac{1}{3}-\cos^2\theta)\left(\frac{c}{r}\right)^3(\tfrac{2}{3}-2\sin^2 d), \\ K &= \frac{3}{2}\frac{S}{M}\left(\frac{a}{c}\right)^3 a = 24{\cdot}7\text{ cm}, \end{aligned}\right\} \tag{6}$$

where S is the mass of the Sun, M the mass of the Earth, a the radius of the Earth, r the distance to the Sun and c its mean value, θ is colatitude on the Earth, and d the (northern) declination of the Sun. The value of z will vary with $\odot$, the longitude of the "mean Sun" ($\odot = 0$, 2π on March 21, $\odot = \pi/2$ on June 21, etc.), because of a variation in the heliocentric distance by (*A.M. of T.*, 5.2*a*)

$$r - c = -0{\cdot}017c\cos(\odot - 282^\circ),$$

and because of changes in the Sun's declination by (*A.M. of T.*, 7.9*a*)

$$\sin d = \sin(23^\circ{\cdot}5)\sin\odot + 0{\cdot}008\sin 3\odot + \ldots$$

due to the obliquity of the ecliptic. The above relationships are only approximate, but they are sufficiently accurate for the present purpose.

The harmonic development in $\odot$ of the product

$$f(\odot) = \left(\frac{c}{r}\right)^3(\tfrac{2}{3}-2\sin^2 d)$$

is (*A.M. of T.*, 7.10*a*, and Table 7.17)

$$f(\odot) = 0{\cdot}026\cos(\odot - 282^\circ) + 0{\cdot}158\cos 2\odot + \ldots$$

plus an additive constant. The above two terms in $f(\odot)$ correspond to the solar annual (Sa) and the solar semi-annual (Ssa) species of the equilibrium tide, respectively. Equation (6) now becomes

$$z = K\tfrac{1}{4}(1 - 3\cos^2\theta)f(\odot). \tag{7}$$

Neither the Earth's crust nor the oceans respond according to the equilibrium theory. The ground is lifted by hz, and the *ocean relative to the ground* by $(1+k-h)z$, where k and h are the Love numbers. The quantity h is related to the rigidity of the Earth, and the factor k allows for gravitational attraction of the tidal bulge on itself. We must also add a correction tide $z'(\odot)$ to the ocean tide $z(\theta, \odot)$ in order that the total tidal volume

$$\int_0 z\,d\Sigma + z'\int_0 d\Sigma$$

integrated over all ocean surface Σ vanishes in spite of the irregular distribution

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[*] Y. Mintz and W. Munk, *loc. cit.*

[†] A. T. Doodson and H. D. Warburg, *Admiralty Manual of Tides*, H.M. Stationery Office, London, 1941. The numbers refer to equations.

of land and sea. When this is done, $(1-3\cos^2\theta)$ in equation (7) is replaced by

$$3(1-D/C)-3\cos^2\theta=0{\cdot}91-3\cos^2\theta,$$

where

$$C=\iint_0 \sin\theta\,d\theta\,d\lambda,\qquad D=\iint_0 \sin^3\theta\,d\theta\,d\lambda,$$

and for future reference

$$G=\iint_0 \sin^5\theta\,d\theta\,d\lambda,$$

are integrals taken over such values of colatitude θ and longitude λ as are covered by oceans. These integrals have previously been evaluated.*

Hence the additive mass per unit surface area due to the Sa and Ssa tides are, for the Earth and ocean,

$$\sigma_e=\tfrac{1}{4}\rho_e hK(1-3\cos^2\theta)f(\odot),$$
$$\sigma_o=\tfrac{1}{4}\rho_o(1+k-h)K[3(1-D/C)-3\cos^2\theta]f(\odot),$$

where ρ_e, ρ_o are the densities of the (homogeneous) Earth and the ocean water. The effect of a heterogeneous Earth will be examined subsequently. With regard to the second expression it can be stated that it appears to give a fair description of the observed ocean tide (relative to the moving crust) from both theoretical and empirical considerations. Rayleigh† has shown theoretically that tides in the actual‡ oceans with periods long compared with a day have nearly the values given by the equilibrium theory (with the above corrections added); and in the case of the lunar fortnightly tide§ an expression equivalent to the above equation is in fair agreement with observations.

So far we have assumed a homogeneous Earth, and hence a displacement at the surface of material of the Earth's mean density ρ_e, whereas the surface rocks have only half this density. However, it would not be correct to take simply half the computed value, as the tidal displacement of internal density layers contributes to the changes in inertia. Apparently a factor ρ_e'/ρ_e allowing for the internal distribution of density must lie between 0·5 and 1·0.

We can estimate this factor by analogy with the (non-tidal) equatorial bulge. For a homogeneous ellipsoid its moment of inertia would equal

$$\epsilon\,.\,\tfrac{2}{5}Ma^2,$$

where $\epsilon=\frac{1}{297}$ is the Earth's ellipticity. The actual value is

$$\epsilon'\,.\,\tfrac{1}{3}Ma^2,$$

where $\epsilon'=\frac{1}{306}$ is a quantity that can be found from the period of the precession of the equinoxes. The ratio

$$\frac{\epsilon'}{\epsilon}\,\frac{5}{6}=0{\cdot}81=\frac{\rho_e'}{\rho_e} \tag{8}$$

represents the reduction in moment of inertia due to concentration of the heavier material nearer the Earth's centre.

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* Walter Munk and Roger Revelle, *loc. cit.*

† H. Lamb, *loc. cit.*, p. 362.

‡ In the case of an ocean covering the entire globe this result probably does not hold.

§ The values for the Sa and Ssa tides cannot be directly compared to observations because of the much larger meteorological effects of annual and semi-annual period.

The expressions for the changes in the moments of inertia and the resulting changes in the length of day become

$$\left.\begin{aligned} \Delta I_e &= a^4 \iint_e \sigma_e \sin^3\theta \, d\theta \, d\phi = \frac{4\pi}{15} a^4 \rho_e' h K f(\odot), \\ \Delta I_0 &= a^4 \iint_0 \sigma_0 \sin^3\theta \, d\theta \, d\phi = \tfrac{3}{4} a^4 \rho_0 K (G - D^2/C)(1 + k - h) f(\odot), \end{aligned}\right\} \quad (9)$$

and

$$\left.\begin{aligned} \frac{\Delta T_e}{T} &= \frac{\Delta I_e}{I_m} = \frac{9}{10} \frac{\rho'_e}{\rho_e} \frac{I}{I_m} \frac{S}{M} \left(\frac{a}{c}\right)^3 h f(\odot), \\ \frac{\Delta T_0}{T} &= \frac{\Delta I_0}{I_m} = \frac{81}{32\pi} \frac{\rho_0}{\rho_e} \frac{I}{I_m} \frac{S}{M} \left(\frac{a}{c}\right)^3 (G - D^2/C)(1 + k - h) f(\odot), \end{aligned}\right\} \quad (10)$$

respectively, where I/I_m is the ratio of the Earth's moment of inertia ($\frac{1}{3}Ma^2$) to that of the mantle. With the numerical values $\rho_e' = 0{\cdot}81\rho_e$, $\rho_e = 5{\cdot}5$ g cm^{-3}, $\rho_0 = 1{\cdot}0$ g cm^{-3}, $I/I_m = 1{\cdot}1$, $S/M = 3{\cdot}29 \times 10^5$, $a/c = 4{\cdot}27 \times 10^{-5}$, $h = 0{\cdot}61$, $k = 0{\cdot}29$, $C = 8{\cdot}79$, $D = 6{\cdot}11$, $G = 4{\cdot}97$, $T = 0{\cdot}865 \times 10^8$ ms, we obtain, in milliseconds,

$$\left.\begin{aligned} \Delta T_e &= 0{\cdot}028 \cos(\odot - 282^\circ) + 0{\cdot}171 \cos 2\odot \\ \Delta T_0 &= 0{\cdot}005 \cos(\odot - 282^\circ) + 0{\cdot}027 \cos 2\odot \\ \hline \Delta T_e + \Delta T_0 &= 0{\cdot}033 \cos(\odot - 282^\circ) + 0{\cdot}198 \cos 2\odot. \end{aligned}\right\} \quad (11)$$

The function is shown by the upper curve in Fig. 4. It represents a nearly semi-annual variation with a slight annual inequality.

6. *Comparison with astronomical observations.*—The heavy curve in the lower part of Fig. 4 shows the computed change in the length of day due to both winds and tides. The circles represent astronomical measurements*, from 1951 January to 1952 September. In terms of the fundamental and first harmonic of the annual variation, the results are (in milliseconds):

Bodily tides :	0·01 cos ⊙	−0·03 sin ⊙	+0·17 cos 2⊙	
Ocean tides :	0·00 cos ⊙	−0·00 sin ⊙	+0·03 cos 2⊙	
Total tides :	0·01 cos ⊙	−0·03 sin ⊙	+0·20 cos 2⊙	
Winds :	0·24 cos ⊙	−0·26 sin ⊙	+0·02 cos 2⊙	+0·02 sin 2⊙
Tides and winds :	0·25 cos ⊙	−0·29 sin ⊙	+0·22 cos 2⊙	+0·02 sin 2⊙
Astron. obs. :	0·19 cos ⊙	−0·26 sin ⊙	+0·35 cos 2⊙	+0·09 sin 2⊙

The agreement between the computed and observed annual terms is surprisingly good with regard to both phase and amplitude. The computed and observed semi-annual terms are roughly in phase, but the observed amplitude exceeds the computed amplitude by fifty per cent. The discrepancy may be the result of errors in the astronomical observations. It may also be due to shifts in the distribution of ocean water.

The discrepancy could be removed by setting $h = 1{\cdot}00$ instead of $0{\cdot}61$ in our calculations, but this falls outside the present estimate of $h = 0{\cdot}61 \pm 0{\cdot}05$. If the discrepancy were observational error, then one might expect that an average based on many years of observations could be used to compute h. The appropriate equation follows from (8) and (10):

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* Humphry M. Smith and R. H. Tucker, *loc. cit.*, Table II.

$$1+k+jh=j'A, \tag{12}$$

where A is the observed amplitude (ms) of the term in $\cos 2\odot$, and

$$1+j=\frac{16\pi}{45}\frac{\rho_e'}{\rho_0}\frac{C}{GC-D^2}=6{\cdot}9,$$

$$\frac{1}{j'}=\frac{81}{32\pi}\frac{\rho_0}{\rho_e}\frac{I}{I_m}\frac{S}{M}\left(\frac{a}{c}\right)^3\frac{GC-D^2}{C}\,0{\cdot}158\,T=\left(\frac{1}{25}\right)\text{ ms.}$$

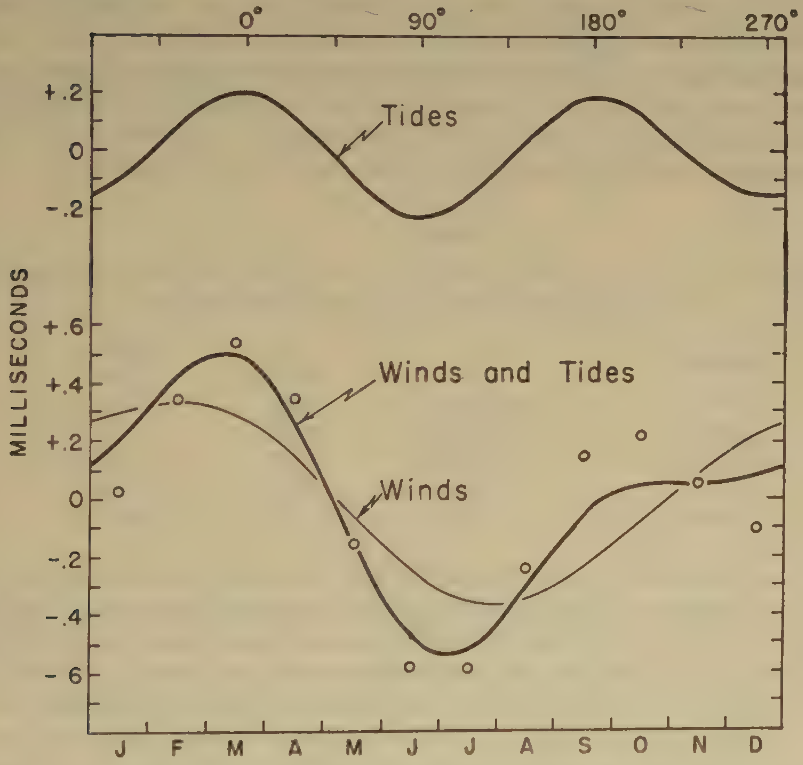

FIG. 4.—*The curves represent the computed variation in the length of day in ms due to tides (equation 11), winds, and the combined effect of winds and tides. The circles refer to the observed values. The scale at the top is given in units of ⊙, the longitude of the " mean Sun ".*

From measurements of long-period ocean tides, we have

$$1+k-h=0{\cdot}68\pm0{\cdot}05.$$

Subtracting this from (12) and dividing by $(1+j)$ yields

$$h=\frac{j'A-(1+k-h)}{1+j}=3{\cdot}62\,A-0{\cdot}10. \tag{13}$$

For $A=0{\cdot}198$ ms (equation 11) we simply recover the assumed value, $h=0{\cdot}61$.

After many years of astronomical observations the accuracy with which A can be determined will be limited by the precision with which we can allow for the effects of winds (and shifts in ocean water?). Suppose the standard deviation in A equals the amplitude of the wind term in $2\odot$, i.e. 0·03 ms. This is about the best one can hope for. The standard deviation in h is then nearly $0{\cdot}03j'/(1+j)$, or 0·11. This is not good enough, for the standard error of the present value is 0·05. The difficulty lies of course in the meteorological contribution to the semi-annual term.

There are other long-period tides which suffer less competition from meteorological and oceanographical factors. A list of long-period tides together with the pertinent data is given in Table II. The astronomical observations give the cumulative time effect $\int A\cos(2\pi t/\tau)\,dt$, whose amplitude is $TA/2\pi$, rather than the variations in the length of day, whose amplitude is A. Although variations in the length of day arising from the lunar fortnightly Mf are over twice those caused by the semi-annual Ssa, the resulting cumulative time effect is only one-sixth as large, and it is doubtful whether it can be detected by present techniques.* The nineteen-year lunar term would lead to a maximum cumulative time effect of ± 0·2 seconds, but the measured deviations from one decade to the next exceed one second. They appear to be the result chiefly of electromagnetic coupling between the mantle and a turbulent core.†

TABLE II

Long-period tides, their period T, the amplitude A of the resulting variation in the length of day, and the amplitude $TA/2\pi$ of the cumulative time effect

Constituent	T	A ms/day	$TA/2\pi$ ms
Mf	14 days	0·43	1·0
Mm	1 month	0·23	1·1
Ssa	6 months	0·20	5·8
Sa	1 year	0·04	2·3
Lunar	19 years	0·18	197·0

It does not appear, therefore, as if tidally induced variations in the length of day can compete with present methods for providing information concerning the Earth's interior. The lunar fortnightly has too short a period to be detectable, the solar annual, and the semi-annual to a lesser extent, are buried by meteorological effects; and the lunar nineteen-yearly by turbulent motion in the fluid core.

7. *Discussion and conclusion.*—Winds and bodily tides are the principal factors contributing to the annual and semi-annual variations in the length of day, respectively. Shifts in air and water masses are of secondary importance.

In this respect the conclusion is opposite to that concerning the annual wobble in the axis of rotation. Here the shift in air mass is the principal factor, and winds are secondary. The difference can be accounted for as follows. The most important mass-shift in the atmosphere is the gain, in winter, of air mass over the Asiatic continent and the corresponding loss over the North Atlantic and eastern North Pacific Oceans. This longitudinal shift alters the *products* of inertia, and thereby the position of the axis, but not the rate of rotation which depends on the *moment* of inertia.‡ On the other hand, the most important change in the angular momentum of the atmosphere is related to the weakening and

* G. M. Clemence, personal communication.

† Walter Munk and Roger Revelle, *loc. cit.*

‡ The reverse is true for the mass shift associated with the bodily tide. The ocean tide, as considered in this paper, gives rise to a very small wobble because of the asymmetry in the distribution of land and sea.

strengthening of the westerly winds. This affects the rate of rotation, but does not contribute appreciably to the wobble because of the zonal symmetry of the winds. The monsoon winds are an exception, and they cannot be ruled out as a factor in the annual wobble of the axis.*

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* Walter Munk and Gordon Groves, " The Effect of Winds and Ocean Currents on the Annual Variation in Latitude ", *Journ. of Met.*, **9**, 385–396, 1952.

ECOLOGY OF FORAMINIFERA AND ASSOCIATED MICRO-ORGANISMS FROM MISSISSIPPI SOUND AND ENVIRONS

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ECOLOGY OF FORAMINIFERA AND ASSOCIATED MICRO-ORGANISMS FROM MISSISSIPPI SOUND AND ENVIRONS[1]

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ABSTRACT

1. Foraminifera *et cetera* have been studied from approximately 400 surface-sediment samples in Mississippi Sound, the marsh and estuaries on the adjacent mainland, the barrier sand islands bounding Mississippi Sound on the south, and the open gulf outside the barrier islands.

2. The microfaunas in this area can be divided into four geographic and ecologic facies, as follows.

a. The open-gulf facies occurs outside the barrier islands and is characterized by being composed mostly of calcareous Foraminifera, principally *Nonionella atlantica*, *Cibicidina strattoni*, *Elphidium*, various Miliolidae, *Discorbis*, and "*Rotalia*" *beccarii* var. Ostracoda are restricted to this facies.

b. The sound facies contains arenaceous Foraminifera, principally *Ammobaculites*.

c. The estuary facies is characterized by an abundance of *Ammobaculites exilis* and *Ammosclaria fluvialis*. *Miliammina fusca* is abundant.

d. The marsh facies is characterized by *Ammoastuta inepta*, *Arenoparrella mexicana*, *Leptodermella*, *Trochammina comprimata*, *T. macrescens*, *Urnulina*, *Haplophragmoides subinvolutum*, and *Recurvoides* sp. *Miliammina fusca* is abundant.

3. A few subdivisions of these facies appear to be somewhat distinctive, as follows.

a. Nearshore barrier-island faunas, generally characterized by low populations of *Elphidium*, Miliolidae, or "*Rotalia*."

b. Barrier-island lake faunas may contain a mixture of marsh and sound species, in some places with open-gulf species.

c. Inner marsh samples are differentiated by abundance of *Leptodermella* and *Urnulna*.

4. There is mixing of faunas, as follows.

a. The open-gulf faunas occur inside inlets between barrier islands and at some places behind the islands, where there is mixing with the sound fauna.

b. The most abundant marsh and estuary species, *Miliammina fusca*, is mixed with the sound fauna near marsh areas, principally near the mainland.

c. Marsh species occur in the estuary faunas, presumably due to mixing, and are most abundant where the estuaries are narrow.

5. The contrast between the open-gulf and the sound faunas is believed to be caused by the islands acting as a barrier to the invasion of the open-gulf water mass into the sound. This is aided by high runoff into Mississippi Sound.

The presence of open-gulf faunas in the sound suggests that the routes of invasion of open-gulf water are along the bottom. Distributions of sound faunas in the open gulf probably reflect average hydrographic conditions.

6. In the San Antonio Bay area, near Corpus Christi, Texas, there are open-gulf and bay faunas similar to those in the Mississippi Sound area. *Elphidium* spp. and "*Rotalia*" *beccarii* vars. occur in the San Antonio Bay fauna. This is believed to be related to the low runoff so that most of the bay is undiluted open-gulf water. Few marsh and/or estuary species occur in the bay fauna.

Atchafalaya Bay, a high runoff area with no barrier island, contains a mixture of bay, open-gulf, and marsh and/or estuary species.

INTRODUCTION

GENERAL STATEMENT

This report is on the distribution of Foraminifera, and some associated larger micro-organisms having hard parts, from Mississippi Sound and nearby marine

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[1] Contribution No. 15, Marine Foraminifera Laboratory. Contribution No. 694, Scripps Institution of Oceanography. Manuscript received, November 4, 1953.

[2] Marine Foraminifera Laboratory, Scripps Institution of Oceanography.
This work is released through the courtesy of Paul D. Foote, executive vice-president of the Gulf Research and Development Company, and Ben B. Cox, director of the Geology Division of that organization. The samples were collected by John C. Ludwick and William Glezan.

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and semi-marine areas. It is based on a study of approximately 400 samples from the area extending from Mobile Bay to Chandeleur Sound. The purposes of this paper are: (1) to define the distribution patterns of the Foraminifera and associated micro-organisms, (2) to interpret these patterns in terms of the known or inferred environmental factors, (3) to compare the distribution patterns with other, similar areas where patterns are known, and (4) to attempt to interpret the results in terms of possible geological applications.

DESCRIPTION OF AREA AND LOCATIONS OF STATIONS

The area includes essentially all of Mississippi Sound, extending from the western boundary of Mobile Bay westward to Gulfport, Mississippi, a distance of approximately 40 miles. The area sampled extends seaward (south) to the 60-foot (10-fathom) contour, a distance of approximately 15 miles in the east and 25–30 miles in the west. The mainland bordering Mississippi Sound on the north is fringed with marsh and marshy islands and is indented with numerous tidal streams or estuaries, many of which are locally called bayous. The principal stream is the Pascagoula River, which enters Mississippi Sound at Pascagoula, Mississippi; this river has tidal influences for a few miles upstream and is fringed with marsh. There are several bays, the largest of which is Biloxi Bay at Biloxi, Mississippi, in the western part of the area. Graveline Bay is near the coast between Biloxi and Pascagoula, Mississippi, and is connected with Mississippi

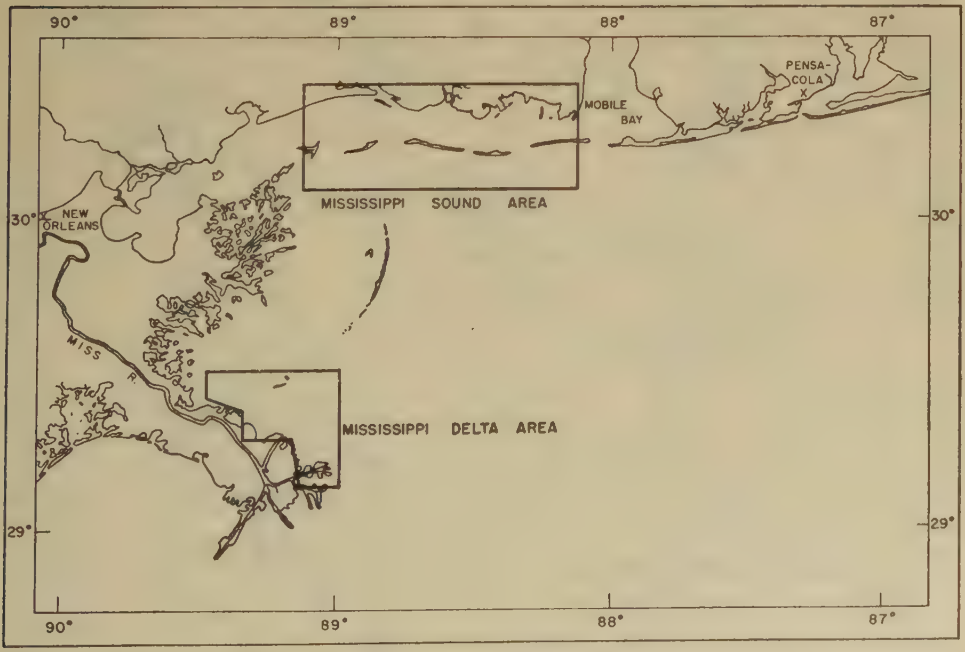


FIG. 1.—Index map showing areas studied.

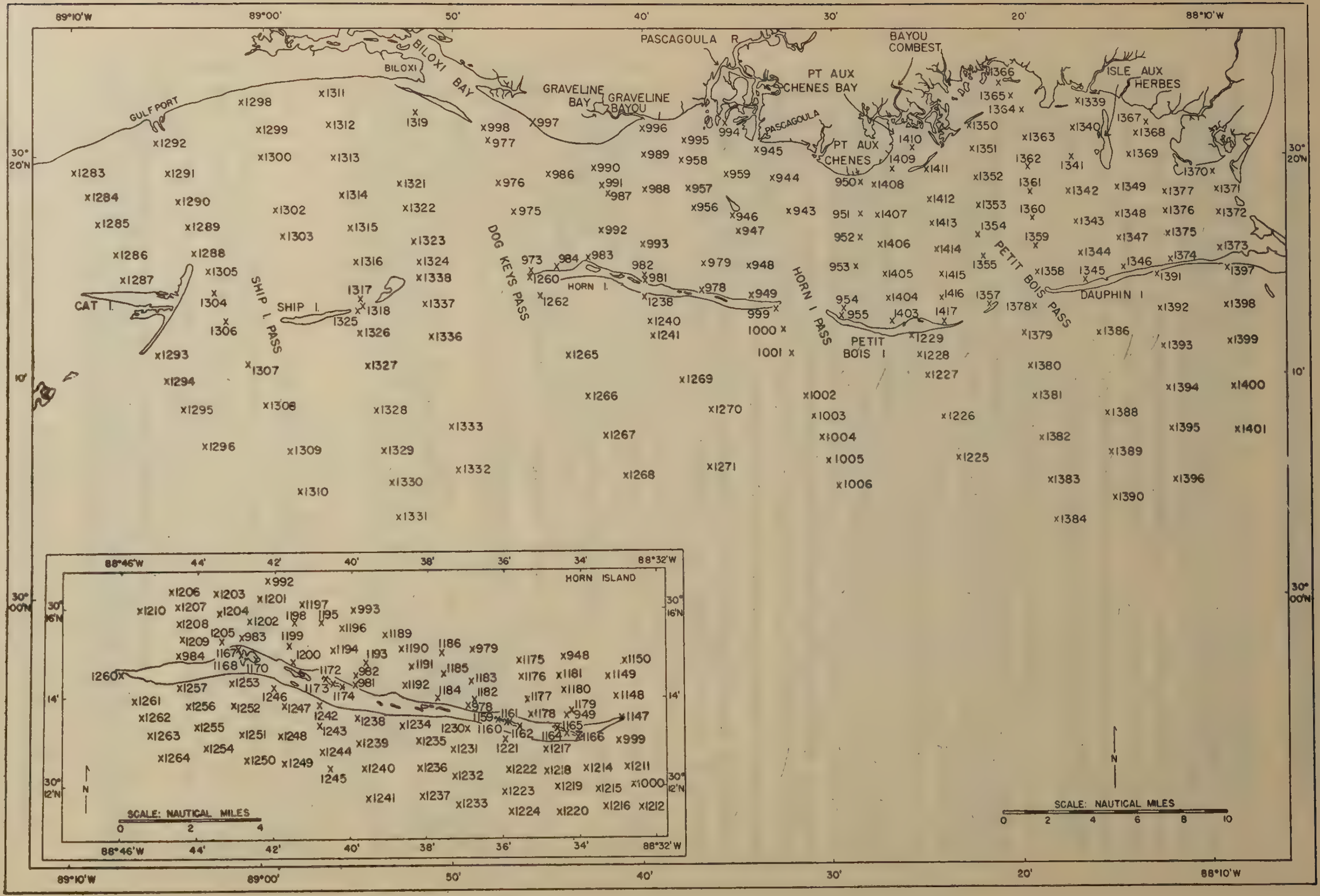

89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
PASCAGOULA R
BAYOU COMBEST
PT AUX CHENES BAY
ISLE AUX HERBES
BILOXI
BILOXI BAY
GULF PORT
GRAVELINE BAY
GRAVELINE BAYOU
PASCAGOULA
PT AUX CHENES
CAT I.
SHIP I.
SHIP I. PASS
DOG KEYS PASS
HORN I.
HORN I PASS
PETIT BOIS I
PETIT BOIS PASS
DAUPHIN I
N
SCALE: NAUTICAL MILES
0
2
4
6
8
10
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
HORN ISLAND
N
SCALE: NAUTICAL MILES
0
2
4

FIG. 2.—Locations of stations in Mississippi Sound and adjacent open gulf.

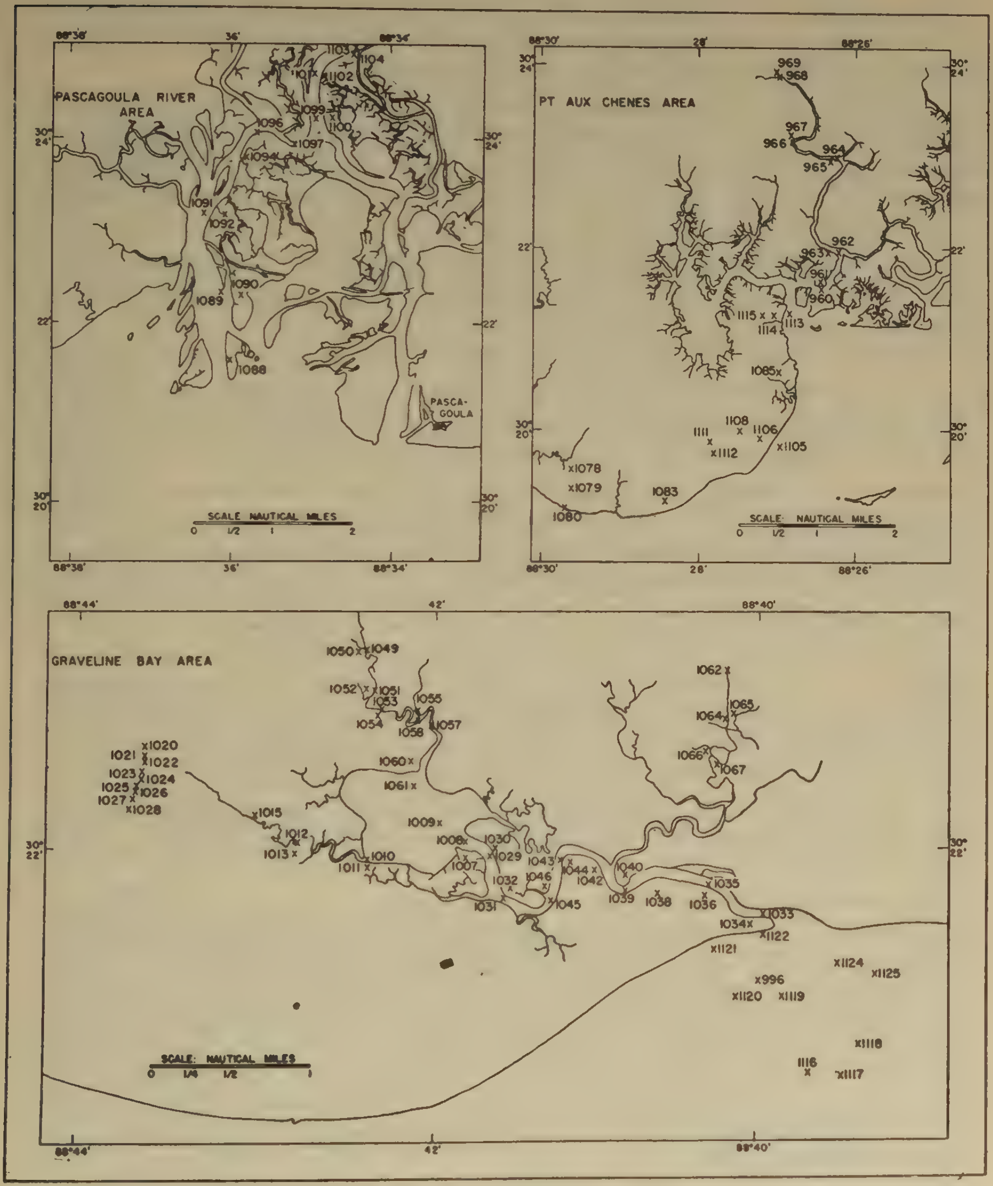

PASCAGOULA RIVER AREA
88°38'
36'
88°34'
30° 24'
22'
30° 20'
1103
1101
1102
1104
1099
1096
1100
1097
1094
1091
1092
1090
1089
1088
PASCAGOULA
SCALE NAUTICAL MILES
0
1/2
1
2
PT AUX CHENES AREA
88°30'
28'
88°26'
30° 24'
22'
30° 20'
969
968
967
966
964
965
962
963
961
960
1115
1114
1113
1085
1108
1111
1106
1105
1112
1078
1079
1080
1083
SCALE NAUTICAL MILES
0
1/2
1
2
GRAVELINE BAY AREA
88°44'
42'
88°40'
30° 22'
1050
1049
1052
1051
1053
1055
1054
1056
1057
1062
1065
1064
1066
1067
1020
1021
1022
1023
1024
1025
1026
1027
1028
1060
1061
1015
1012
1013
1009
1008
1030
1029
1010
1011
1007
1043
1044
1042
1040
1032
1046
1045
1039
1038
1036
1035
1031
1033
1034
1122
1121
1124
1125
996
1120
1119
1118
1116
1117
SCALE: NAUTICAL MILES
0
1/4
1/2
1

FIG. 3.—Locations of stations in marsh and estuaries.

Sound by a short tidal stream, Graveline Bayou. Other bays of interest are Point aux Chenes Bay and Grand Bay, east of the Pascagoula River. The marsh ends a short distance inland from the coast where there is an abrupt and widespread rise of a few feet to an older surface of deposition and/or erosion.

Mississippi Sound is bounded on the south by a series of sandy, barrier islands. The largest of these is Horn Island, due south of Pascagoula, Mississippi. East of Horn Island are Petite Bois and Dauphin islands, and at the west lie Ship and Cat islands. These are low islands with dunes rising a few feet above sea-level and there are small lakes and areas of marsh on the surface. The islands are separated by inlets, locally called passes. In some places there are low areas extending from south to north across the islands where storm seas apparently have overflowed the surface and cut channels.

The sides of the islands descend rather abruptly to the floor of Mississippi Sound on the north side, where the depths are more than 20 feet in places, especially back of Horn and Petite Bois islands. The average depth of the southern half of Mississippi Sound is approximately 15–20 feet, except for locally deeper troughs near the islands and inlets. The northern half of the sound is generally less than about 10 feet in depth. There are local irregularities in bottom contour in many places. On the seaward side, the islands slope abruptly to depths of about 20 feet within less than ½ mile and slope gently with only minor irregularities to the 60-foot contour.

The locations and numbers of stations are shown on Figures 1, 2, and 3. The stations in the sound and open gulf are spaced in a series of traverses averaging 1½–2 miles apart; there are 12 traverses in the open gulf and 21 traverses in Mississippi Sound. In addition, there is a much denser spacing for approximately 2 miles both south and north of Horn Island, where there are 12 traverses 1 mile apart with stations approximately ¼ mile apart. Several beach samples were collected from Horn Island, and samples also were collected from the lakes on Horn Island.

Abundant samples were taken from the marsh and streams. These samples were spaced as closely as time permitted. Most of the samples along the streams are spaced in pairs, with one sample from the bed of the stream and another from the near-by marsh. The areas sampled in this fashion are around Graveline Bay, along the lower section of the Pascagoula River, and the Pt. aux Chenes area. A line of closely spaced samples was taken from the inner marsh west of Graveline Bay. Several samples were collected from the marsh on Pt. aux Chenes. Several closely spaced samples were taken from Mississippi Sound near the outlet of Graveline Bayou.

METHOD OF STUDY

Most of the samples in the sound and open gulf were collected with a small coring tube designed by Phleger (1951, p. 3). This sampler obtains a short core which is emplaced in a plastic liner tube having an inner diameter of 1⅜ inches.

Table I. Occurrences of Foraminifera, et cetera, in Graveline Bay Marsh. Foraminifera in Percentage of Total Population.

GRAVELINE BAY AREA MARSH																																					
STATION	1007	1008	1009	1010	1011	1012	1013	1015	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1038	1039	1040	1042	1043	1044	1126	1127	1128	1129	1130	1131
TOTAL POPULATION FORAMINIFERA	4,500	5,400	2,000	8,400	1,650	9,100	10,300	5,900	1,850	420	1,125	Abund.	1,200	200	130	260	2,400	5,850	2,600	3,100	3,900	580	3,600	4,200	5,400	1,100	11,600	2,400	7,200	1,500	3,200	6,800	1,800	1,500	2,300	3,100	6,400
Ammoastuta inepta	15			.5	5	5	2	27											26		7		5	1	2	9	.6	2	.6		1				2		.5
Ammobaculites exiguus			2				.1														2						1		.7			2		2			1
A exilis	4	44	20	24	2	19	6											4		6	2	14	4	16	1		2	2	.4	19	.5						.5
A salsus		2	2	3		.3	.5											18		5	1	3	1	19	2		4	6		4		1					4
A sp.		34	67	31	15	31	10	2			1			8				53		52	11	24	13	37	5	1	63	17	6	9	.5	9		26			5
Ammoscalaria fluvialis	4	10	9	9	9	3	5	3									1	16	4	28	12	19	18	5	24	10	28	21	8		27	2	19		2	9	2
Arenoparrella mexicana	66			.5	2	1	.2	1											21		14		1	1	.2	4	.2		.4		5	36	40	2			1
Haplophragmoides subinvolutum	17			.2	1	.4	.3	24					1				1					5	.4	1				1							10		
Leptodermella variabilis					1		2	1	30	31	37	A	60	38	25	6	64	.6				3	.6		1			2	1	4	1						
Miliammina fusca	27	9		34	65	39	72	34			1					13		9	45	7	51	32	57	13	64	74	2	43	83	64	55	47	38	70	63	90	87
Proteonina lagenaria									10							R	24																				
Recurvoides sp	2							2								6																					
Trochammina comprimata	.4				3	.3	1	2	1										4		1							4	.4		3	1			.8		
T. inflata	.3																				1										3	4			3		
T. macrescens	3			.2		.4	1	2			2								.3		.5				1	1		1			2						
Urnulina								.3	48	69	59	C	39	54	75	44	3						1		.2												
Diatoms																																					
Coscinodiscus	R	R	R	R	R		R		R	R	R			R	R	R	R	R	R	R	R	C	R	R	R	R		R	R	R	C	R	R	R	C	R	R
Triceratium	R														R							R									R						
sp. 1	R		R	R	R	R	R	R	R						R	R				R			R		R	R			R		R		R		R		R
sp. 2																																			R		
sp. 3	R					R				R	R					R	R		C		R	R	R														
Fecal pellets		A	A	A														A				A		R	R		C	R		R				A	R		C

Many samples also were taken by forcing the plastic liner tube into the sediment by hand. Where the coring tube is used it is kept upright during sampling so that there is little or no mixing of material. The upper centimeter of the core is placed in a small glass jar together with sea water from directly above the sample, enough neutralized formaldehyde is added to make a 5–10% solution, and also a small amount of baking soda is added to maintain a mildly basic condition in the sample.

In the laboratory each sample was split into two approximately equal parts while still wet. One half was stored, and the other half was washed over a brass sieve having an average opening of 0.074 millimeter. The sample was divided by using a microsplit described by Parker (1948) and a fraction of approximately 300 specimens was counted. In samples having less than about 300 specimens the entire population was counted.

Foraminifera population data are listed in Tables I–X. The total benthonic population is given for each sample and the species are listed as per cent of total population. A few rare species have been deleted from these tables as being of little or no value in the present study. Planktonic Foraminifera are recorded as estimated total number of specimens for each species identified.

Abundances of ostracods, diatoms, and fecal pellets also are recorded, in less detail than were the Foraminifera. These are listed on Tables I–X. Total popula-

Table II. Occurrences of Foraminifera, et cetera, in Graveline Bay Marsh and Mouth of Graveline Bayou. Foraminifera in Percentage of Total Population.

	GRAVELINE BAY MARSH AREA																				MOUTH OF GRAVELINE BAYOU									
STATION	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1057	1058	1060	1061	1062	1064	1065	1066	1067	996	1116	1117	1118	1119	1120	1121	1122	1124	1125
TOTAL POPULATION	3,200	4,400	1,900	4,000	16,200	1,800	6,400	10,800	11,400	14,500	10,400	2,000	300	2,300	5,600	7,700	18,000	7,500	20,000	8,200	4,400	6,800	8,100	740	1,000	1,900	3,400	5,400	1,300	6,500
Ammoastuta inepta		1	3	33	1	13	1	4	.6	25	.3	1	11	8		8	3	21	1	7								.6	5	
Ammobaculites dilatatus																					7	3	5	9		2				
A. exiguus															.6									4	3			.6		7
A. exilis	17	4	65	2	70	3	80	1	39	1	30	16			22	49	59		46	13		1		4		2	5	5		1
A. salsus	2	2		.4		.4		1	11	.2	5	2			9		.5		18	.3	45	40	20	39	6	19	18	22	20	9
A. sp.	22	9		.4	13	7	2	.3	14	1	4	9			20		2		12	11	32	44	60	9	31	19	18	16	30	13
Ammoscalaria fluvialis	46	8		4	.6	2		26	.6	7	2	10	11	4	16		2	3	3	2			7				9		5	1
Arenoparrella mexicana	1	.7			.6	14	.5	2	1	2	.3	.3	22	1		4	3	7	5	3								3		
Gaudryina exilis																							.5							
Haplophragmoides subinvolutum				1				.2								2		.2	.3											
Leptodermella variabilis		.4	15	6		2		1	.3	1	.6					.5	.2	.2		.7										
Miliammina fusca	11	73	8	44	14	43	16	62	32	59	58	61	33	87	32	36	29	63	14	69	15	13	7	35	60	58	50	53	40	69
Recurvoides sp.				2	.3	1	.2			.2						1		.4	.7											
Trochammina comprimata		.7		1	1	6		1	1	3		.3	22			7	1	4	1	2										
T. inflata				.4														.4		.3										
T. macrescens		1	1	3		8	.2	1	.3	.4		.3				4		1	.7	2										
Urnulina			7	4	.3							.3				2														
Diatoms																														
Coscinodiscus	R	R	C	R	R	R	R			R	R	R	R	R	R	R	R	A		C	R	R	R	R	R	R	R	R		
Melosira																									R					
Triceratium		R																				R								
sp. 1	R		R	R		C										R	R	C		R								R		
sp. 2																						R		R				R		
sp. 3						R						R																		
Fecal pellets							R		C		C	A			A				R		A	R	R	R	R	A	R	A	R	R

tions of Ostracoda were counted but no attempt was made to differentiate species. This procedure was adopted because the Ostracoda seem to be more or less uniformly distributed regardless of type. Six types of diatoms were separated and recorded as abundant (A), rare (R), or common (C). Some of the groups of diatoms probably contain more than one species. A few other diatoms were recognized but were not recorded. The approximate relative abundance of fecal pellets is recorded as abundant, common, and rare.

BIOFACIES

Distributions of several of the species and species groups of Foraminifera and associated micro-organisms are summarized on Figure 4. Study of this figure, together with distributions shown on Figures 5–28 and in Tables I–X, shows that four biofacies are present in the Mississippi Sound area. Two or more subfacies are superimposed on this pattern. It is possible that several subfacies could be justified on the basis of the distributions, but it is believed that the following simplified division gives the major framework of the facies distributions.

TABLE III. OCCURRENCES OF FORAMINIFERA, ET CETERA, IN PASCAGOULA RIVER AND MARSH AND PT. AUX CHENES AREA. FORAMINIFERA IN PERCENTAGE OF TOTAL POPULATION.

	PASCAGOULA RIVER AREA														PT. AUX CHENES AREA																						
STATION	1088	1089	1090	1091	1092	1094	1096	1097	1099	1100	1101	1102	1103	1104	960	961	962	963	964	965	966	967	968	969	1078	1079	1080	1083	1085	1105	1106	1108	1111	1112	1113	1114	1115
TOTAL POPULATION FORAMINIFERA	7,800	15,800	3,500	1,250	3,900	4,500	2,800	250	5,000	2,100	6,100	2,300	<30	2,100	930	700	3,700	3,500	4,000	1,200	2,600	6,300	850	4,800	1,600	2,300	30	160	1,300	<30	860	690	2,700	3,600	640	2,200	2,400
mmoastuta inepta	.4		19	3	25	9	6		3	6	1	33		3						3		7		6										7			
mmobaculites dilatatus															14																						
exiguus				3		.7					.5				7													5				5					
exilis	1	30		17	1	2	2		47	3	27	1		23		2	8		20		20	2	13					15				2					.6
salsus	4	27	1		.4	3	2		7	.3	16			4	35	2	10		2		5	1	2	1				10				2	5		50	3	
sp.		3	1	15	1	12	9	50		3	14				10	18	41	9	20	3	9	11	11		11			40				14	3		40	7	
mmoscalaria fluvialis	30	3	2	23	2	21	2		3	3	3	5		1	10	9	13	3	11		2	3	11	5	5	3		10			14	23	18	16		9	5
renoparrella mexicana	4	.2	2		1	.7										5	.4	35		43		9	2	3	2				58					.4		8	5
audryina exilis						.4																														2	
alplophragmoides subinvolutum									1	.3						1		.4		4		.5					100										
agunculina vadescens																																2					
eptodermella variabilis							1		1	5		2		3		2			1		.5	2	2	6		.7		5			4	5		2			
iliammina fusca	60	36	72	36	63	51	72	50	36	75	34	55		48	21	16	38	47	46	20	63	55	56	76	77	88		15	38		61	30	74	55		69	88
roteonina lagenaria					1				1					3																							
sp. A							.6																														
ecurvoides	.4	.2		3	.4	.4					.5																							7			
eophax																1		2																			
rochammina comprimata			1		1											29		5		12		8		3	6	8											3
inflata			.5													15		.5		7		.5							4							1	.6
macrescens			1		4		2		1	1		2		3	3	1				8		1		2		.7					11	10		10		1	1
rnulina							3			3	3	2		12																		5					
Diatoms																																					
oscinodiscus	C	R	R	R	R		C	R	C	R	R	R	R	R		R	R	R	R	R	R				R	R	R	R	C	R				R	R	R	R
elosira				R			R																														
riceratium					R		R					R																									
1					R		C		R	A				R			R		R	R		R			R											R	
2																														R							
3	R							R				R		C																							
Fecal pellets	R			R					R		R						R		C						A					R							R

OPEN-GULF FACIES

The open-gulf facies extends seaward from the barrier islands and its western border is approximately at Ship Island. The fauna is characterized by the following general features.

1. Ninety per cent or more of the Foraminifera population commonly is composed of calcareous species.
2. There is a larger number of Foraminifera species than in the sound facies.
3. Presence of abundant Ostracoda.

The following species are restricted to the open-gulf facies except where there is faunal mixing in Mississippi Sound near inlets and at a few other places to be discussed.

Asterigerina carinata
Bigenerina irregularis
Bolivina lowmani
B. pulchella var. *primitiva*
B. striatula
Buliminella cf. *bassendorfensis*

Table IV. Occurrences of Foraminifera, et cetera, in Mississippi Sound. Foraminifera in Percentage of Total Population.

MISSISSIPPI SOUND																																					
STATION	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	973	975	976	977	978	979	981	982	983	984	986	987	988	989	990	991	992	993	994	995
TOTAL POPULATION FORAMINIFERA	1,800	300	6,000	300	2,600	2,300	30	300	500	1,000	1,500	30	100	140	200	800	600	<75	1,700	200	600	160	350	30	200	<15	60	900	60	220	3,100	170	6	550	800	2,500	4,400
Ammobaculites exiguus	7	3	1				50			19					4	4											50	2			27			5	8		1
A exilis			.5																																	52	
A dilatatus			2																		13				2												2
A salsus	24	13	32	50	2	23			57	66	52			23	26	48	5		15	25	58		45		21			26		21	1	5		42	36	35	30
A sp	65	76	16	30	5	74		55	33	9	46			77	63	12	82		26	42	8		45		63			60	100	76	62	43	67	42	32	8	24
Ammoscalaria fluvialis		3	.5	20					10								3		3	4	8		10	100				2			3	50	33	3			
Bolivina lowmani					1																																
Buliminella elegantissima					4																																
Discorbis cf columbiensis					1																																
Elphidium delicatulum								12																													
E galvestonensis													33																								
E gunteri					5			33					33									100															
E incertum					10														2		3																
E matagordanum							50												1																		
E poeyanum					1															4																	
Gaudryina exilis		3			1					3							2		4						4					2	1			6	4		
Haplophragmoides subinvolutum																					3																
Leptodermella sp																																					1
Miliammina fusca		5	48												7	36	5			4							50	9			7	2				8	41
Nonionella atlantica					1														1																		
Proteonina sp A	4					3				3	2								4						10					1				6	16		
Reophax						3			2	3																					1				4		
"Rotalia" beccarii vars					69							100	33						45	21	8																1
Urnulina difflugiformis		2																																			
Ostracoda					30		30	160					30										30						5								
Diatoms																																					
Coscinodiscus	C	C	R	R	R		R	R	C	A	A	R	R	A	A	R	R		C	A	R		C	R	A		R	R	A	A	C	A	A	C	C	R	R
Melosira	R		R		R			R		R	R			R			R						R		R			R		R	R			R	R		
Triceratium	R	R	R		R					R	R	R		R					R	R			R		R				R	R		R	R	R			
sp 1		R															R		R										R	R		R	R	R			
sp 2	R		R	R					R		R			R	R		R			R	R				R		R	R	R	R		C	R	R			R
sp 3								R									R		R		R										R				R		
Fecal pellets	A	A	C				R	R	A	A	A	R		A	A	R	A		A		A		C	R	A		R	A	A	A	A	A	A	A	A	A	C

B. elegantissima
Cibicidina strattoni
Discorbis cf. *columbiensis*
D. floridana
Elphidium spp.
Eponides hannai
Guttulina australis
Miliolidae
Nonionella atlantica
N. opima
Proteonina atlantica
Reussella atlantica
"Rotalia" beccarii vars.
"R." rolshauseni
Textularia cf. *mayori*
Virgulina pontoni

Cibicidina strattoni and *"Rotalia" beccarii* vars. are the most abundant species in this facies, together constituting half or more of the fauna at most open-gulf stations.

Planktonic Foraminifera occur in the open-gulf fauna in this area at less than half the stations and in very low frequencies. The most common species is *Globigerinoides rubra*, which has been shown by Phleger (1951) to be the dominant planktonic species in the Gulf of Mexico. *Globigerina bulloides* also is present at a few stations, numerous small globigerinids have been found, and *Orbulina universa* occurs in one sample. The abundances of planktonic Foraminifera are comparable

Table V. Occurrences of Foraminifera, et cetera, in Mississippi Sound.
Foraminifera in Percentage of Total Population.

	MISSISSIPPI SOUND																																						
STATION	996	997	998	1147	1148	1149	1150	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208
TOTAL POPULATION FORAMINIFERA	4,400	8,300	850	30	600	600	700	130	30	350	<30	800	700	2,900	1,800	<30	190	<30	100	<30	250	2700	600	2,500	130	800	5,500	5,500	300	700	300	600	1,200	15	3,000	1,400	2,200	2,200	2,100
obaculites dilatatus	7	2																																					2
exiguus			4			5	9			2		4	3	2	1						25	6	2	3	75	38	9	14	22	9			8	14	9	2	1	6	2
exilis		1																									1							14	1				
salsus	45	24	11					50	50	18		4	77	7	48		54		33			33	18	26		21	14	10		5		95	11		29	21	13	7	4
sp.	32	63	75						50	3			3	2	39		38		33		25	47	61	55	25	33	58	11	11	23	10		22	28	33	58	34	44	13
oscalaria fluvialis			8							52		55		6	3							5	2	2											1		3	6	
oparrella mexicana		.3	2																																				
rigerina																												.5											
inella elegantissima														1														2									6	4	
idina strattoni					39	15	9																																6
rbis cf. columbiensis					6																																		
floridana																																							2
dium discoidale														3																									
gunteri					6	25	27																								30		3						10
incertum	1				10	15								2														1							3			3	
poeyanum						5																					.5												2
translucens							4																					.5											
sp.							9														25										10								4
ryina exilis							4			9		6	11	4	3		.5					7	3	6			5	4		5			3		3	9	1	6	
lina australis					6																																		
ophragmoides subinvolutum		.3																																					
lidae				100	27		19														12																		
mmina fusca																																							
nella atlantica	15	8						25															.6				1	.5				5				2			
onina sp A										16		29	3	1	8		8					2	10	6			2								5	5	9	4	
nammina comprimata																							3	1											1				
inflata																													11										
laevigata						10																				8	4	3					3						
macrescens													2										.6																
hax																			33				.3	1											1				
id° beccarii vars						20	19	25				2		71													6	52	55	59	50		52		13		33	20	51
lina																																		14					
tracoda					300		200												30		30				30			320							30				300
toms																																							
nodiscus	R	R	C		R	R	R	R	R	A	R	A	A	C	A	R	A	R	R	R	R	A	A	A	R	C	A	C	C	R	R	A	R	R	C	A	A	A	R
sira										R		R	R	R	R		R					R	R	R			R	R			R				R		R	R	
re ium										R		R		R	R		C			R		R	C	R		R	R	R	R		R		R	R	R	R	R	C	R
1										R		R										R	R	R													R	R	
2																	C					R	R			R		R				R			R				
3																					R										C								
ca: pellets	A	C	R		R	R	R	R	R	A		A	A	A	A		A		R	R	R	A		A	R	R	A	R		R		A	R	R	C	A	A	A	R

TABLE VI. OCCURRENCES OF FORAMINIFERA, ET CETERA, IN MISSISSIPPI SOUND. FORAMINIFERA IN PERCENTAGE OF TOTAL POPULATION.

	MISSISSIPPI SOUND																																		
STATION	1209	1210	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296	1298	1299	1300	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317
TOTAL POPULATION FORAMINIFERA	60	200	80	60	150	250	<15	80	400	40	170	350	100	60	900	400	60	500	300	200	300	15	300	350	4,800	30	360	260	6,000	700	900	800	200	500	>10,000
Ammobaculites dilatatus			7	7												4		.4	3	1				8			1	3	11	.5	1	1			
A. exiguus		17				3			1						2	12		.4			4	13					1		.3	1	1	3	4	3	
A. exilis														100															.3						
A. salsus			29	55	47	43		60	48	10	15	38			63	56	50	41	16	17	51	66		19			1	30	43	52	43	48	34	36	
A. sp.			59	28	50	36			41	67	81	60			25	20	50	57	72	17	51	66		19			1	30	43	52	43	48	34	36	
Arenoparrella mexicana												1																							
Bigenerina irregularis																																			1
Bolivina lowmani															2	4							10		1										
Buliminella bassendorfensis																							10		5										1
B. elegantissima	50																						10		8										
Cibicidina strattoni													33										20		.6										17
Discorbis cf. columbiensis																							10		2										1
D. floridana																																			2
Elphidium discoidale																							10												
E. gunteri		17											33												12										1
E. incertum																									1		1								9
E. koeboeense																									.3										
E. poeyanum																									.3										1
E. translucens																									.3										
E. sp.															2								20	2	2										
Eponides hannai																									.3										
Gaudryina exilis				3				20							2	4		.4	1	1	3	13		10	1		1	6			.4	3		6	1
Miliolidae															2																				
Miliammina fusca			4	7	3	10			9	23	1				2			1	5	60	1			2				1	2	1	15	2	4		
Nonionella atlantica																									5										13
Proteonina sp. A.								20	.5												8				1		3	1		.4		1	2		
"Rotalia" beccarii vars.	50	17				2							33						1			13	10		58			1							50
Urnulina difflugiformis											3																								
Virgulina pontoni																									1										
Ostracoda		160																							60										1950
Diatoms																																			
Coscinodiscus	R		A	A	A	A		R	A	C	A	A	R		R	C	R	A	A	A		R	R	A	A	A	A	A	A	A	A	A	A	C	R
Melosira	R					R													R			R			R	R		R			R				
Triceratium			R	R	C				R	R	R	R			R	R				R				R	R	R	R	R	R	R		R	R	R	
sp. 1					R	R			R	R	R				R							R		R											
sp. 2						R			R	R	R	R						C											R					R	
Fecal pellets	R		A	A	A	A	R		A	A	A	A			R	R		A	A				R	A	A	A	A	A	A	A	A	A	A	A	

TABLE VII. OCCURRENCES OF FORAMINIFERA, ET CETERA, IN MISSISISPPI SOUND.
FORAMINIFERA IN PERCENTAGE OF TOTAL POPULATION.

	MISSISSIPPI SOUND																																						
STATION	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1339	1340	1341	1342	1343	1344	1345	1346	1347	1348	1349	1350	1351	1352	1353	1354	1355	1357	1358	1359	1360	1361	1362	1363	1364	1365	1366	1367
TOTAL POPULATION BENTHONIC FORAMINIFERA	700	500	400	4,100	70	>10,000	>10,000	4,500	8	<30	<30	2,300	700	330	160	280	300	350	2,400	120	700	1,100	900	3,100	600	30	400	340	1,600	>10,000	200	160	240	550	5,900	600	1,600	2,200	6,600
mobaculites dilatatus	2							.3				1	5	5		2					2	2		1							1		2	1		.5		3	1
exiguus	.6	3	6						25			1							1			2	3	.5	5						2	1	2		.5		2	1	.2
salsus	53	49	63					2	25			60	30	25	44	52	49		43	15	39	40	69	59	38		41	19	12	3	60	37	46	43	54	50	52	41	56
sp.	43	34	19				.3	.2				35	65	69	56	46	46		55	82	59	55	29	39	57		52	48	4	1	29	56	42	55	45	50	34	29	38
enoporrella mexicana																			.3																				
erigerina carinata						.5	.3																							.3									
enerina irregularis				2			1																							.3									
livina lowmani							1	1																															
iminella cf. bassendorfensis							3	6																					2	1									
elegantissima						.5	6	2																				5		2									
icidina strattoni				36	33	10	6																						25	1									
corbis cf. columbiensis						.5	2	.2																						3									
floridana							1	.2																						1									
hidium advenum							.3																						2										
discoidale						.5	1	3																					2	.6									
gunteri				3	33	8	28	2										85											8	4									
incertum				14		25	.3	16																					8	18									
poeyanum				17		20		1																						2									
translucens																		7																					
tumidum						2	1	1																						1									
sp.							.6	2																															
udryina exilis	1	4	1					.5	25					1			1		.3	1	.5	.2		.5		100	7	9			10	6	7		2				
tulina australis				3		.5																								.3									
olophragmoides subinvolutum				2																																			
olidae					33	4	5	8																						2									
iammina fusca												4					4		1		1	3	7														13	26	5
nionella atlantica				6		5	9	12																					8	2									
teonina sp. A	.6	6	9					.2	25																								2	2					
alia" beccarii vars.				18		22	27	39																				14	14	56									
gulina pontoni								.2																						.3									
Planktonic Foraminifera																																							
obigerinoides rubra				160		130																																	
sacculifera											30																												
dentified globigerinid							60																																
Ostracoda				[illegible]			[illegible]	100																				15	160	[illegible]									
Diatoms																																							
scinodiscus	A	R	C		R	R	R	R	R	R	R	A	A	A	C	A	A	R	R	C	A	A	R	C	R	R	R	C	R	A	A	A	C	A	A	A	R	R	
losira	R												R	R			R			R	R	R								R	R	R		R		R			
ceratium	C	R	R									R	R	R	R	C	R		R	R	R			R		R	R	R		R	R	R	R	R					
	R													R						R	R																		
2	R		R									R					R							R												R			
Fecal Pellets	A	C	A				R	R	C		R	A	A	A	A		A			A	A	A		A	R	R	R	A	R	C	C	A	A	A	A	A	R	R	R

TABLE VIII. OCCURRENCES OF FORAMINIFERA, ET CETERA, IN MISSISSIPPI SOUND. FORAMINIFERA IN PERCENTAGE OF TOTAL POPULATION.

	MISSISSIPPI SOUND																																			
STATION	1368	1369	1390	1391	1392	1373	1374	1375	1376	1377	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	1414	1415	1416	1417	1159	1160	1161	1162	1164	1165	1166	1167	1168	1170	1172	1173
TOTAL POPULATION FORAMINIFERA	4,900	10,000	1,200	10,000	6,000	6,300	4,900	500	4,500	4,900	80	15	600	800	1,200	1,200	1,000	1,200	750	2,000	430	940	2,000	10,000	180	130	900	400	450	70	300	130	250	100	1,400	60	1,280
Ammobaculites dilatatus	.3	.2			2	3	1		.3	1								4	6	2		2															
A. exiguus			.3						.3	1	20	50		1	11	4	1	1		8	7	12	2	2					18	3							
A. exilis																										25	41	70		14	90		87				
A. salsus	80	85	62	81	59	60	73	9	14	70			68	62	70	78	66	60	72	79	89	29		2						5		13					
A. sp.	16	14	32	17	37	36	26	88	85	27			15	30	15	14	31	35	22	8	4	52	14		9		14	26	82	44		87		67		50	16
Ammoscalaria fluvialis																														17	10						
Arenoparrella mexicana					.3				.3																												
Bigenerina irregularis																								.7													
Buliminella bassendorfensis																																					
B. elegantissima								.3															3	2													
Cibicidina strattoni											20												3	2	19												
Discorbis cf. columbiensis																								2													
D. floridana																								3													
Elphidium discoidale																								.7													
E. gunteri																							6												11		6
E. incertum																							5	5											9		
E. translucens																							2														
E. sp.											20												2		9												2
Gaudryina exilis		.2							.3				1	2	4							3	2					4									
Guttulina australis																									9												
Leptodermella variabilis																														3							
Miliolidae																								2	9										16		
Miliammina fusca	4	.4	5	2	2	1	.2	1	.3	2							2			1						75	45			3							
Nonionella atlantica								.3		.5													2	9													
Proteonina sp. A													15	5									3														
"Rotalia" beccarii vars.											20	50											53	65	45												
Reophax								.3					1	.2																							
Trochammina inflata																																	13				
Urnulina																														3							
Ostracoda											80	15												2400	15								30	30	160		
Diatoms																																					
Coscinodiscus	R	C	C	R	R	R	C	A	A	A	C	R	A	A	R	A	R	A	R	R	C	C	R	R	R	R			R	R		R			R	R	R
Melosira					R		R					R	R	R		R		R					R						R								
Triceratium	R	R	R		R			R		R		R	C	C	R		R	R			R	R										R					
sp. 1										R						R	R	R	R																		
sp. 2								R					R					R																			
Fecal pellets	A	R	A	R	A		A	A	A	A	R	R	A	A	A	A	A	A	A	R	R	A	C										R		R	C	R

TABLE IX. OCCURRENCES OF FORAMINIFERA, ET CETERA, IN OPEN GULF.
FORAMINIFERA IN PERCENTAGE OF TOTAL POPULATION.

	OPEN GULF																																										
STATION	999	1000	1001	1002	1003	1004	1005	1006	1211	1212	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246
TOTAL POPULATION BENTHONIC FORAMINIFERA	<30	3200	1000	900	300	1500	7200	6700	2200	>10,000	1000	<30	1000	3100	10,800	8000	8600	2900	>10,000	3300	360	4100	4700	300	2700	30	30	5000	5700	4200	9300	2200	2200	9100	7000	6800	5400	4900	130	200	600	4500	100
oboculites dilatatus								.6														6	1													.2	1	1					
exilis		1																																									
salsus															.6				.2	.5							100	1			.3			.4								1	
sp.		1						.6							.3				.2		1				1			1		.2	.3	1	.3			.4	2	.7		48		2	
rigerina carinata		1						.6						4	.6		.4	7	.2	1	1	2	2		1			1	1			3		.4		1	1						
nerina irregularis		2	3		33	4	4	2		.4				2	1	5	2	2	2	2		5	10		5			6	1	.2	.3	4	2	2		3	3	3			8	6	
ina lowmani										1	3				.6		2		2	1	2								2	1	1		2			1	1					1	
striatula var. spinata									1											.5									1				1	1									
pulchella var. primitiva															.3								1					1		.2			.3	.4									
ninella cf. bassendorfensis							.4		1	1					.3	.5			2	3									1	3	5		3	2		2	.6	1			3	1	
elegantissima		4	3				.4		1	1				1	2		.7		4	6	1		1					1	1	.2	5	3	2	1		3	1				3	1	
cidina strattoni		29	23	18	56	64	60	61	36	21	20		52	20	12	14	11	28	3	5	2	52	24		29			23	6	1	3	24	10	15	22	10	18	18	25	17	16	20	
orbis cf. columbiensis		7	6	3	11	2	17	3	1	4	10		3	4	10	1	14		11	7	1	2	7	11	2				7	8	1	1	.6	10		10	4	1			3	2	
floridana		1		3			2	4						1	.6		3	2	.4	.5			1		1			1	1	.5			1	.4		1		.7					
idium advenum															.3														1									1			3		
delicatulum																	.4		.2										4														
discoidale								.6	5		3		6	2	2	.5	3	2	.7			3			2	100		5	1		.7	1	.3	.4	4		.6	2				2	
gunteri		14	3					1		9	3		3		10	.5	5	11	6	6		2	3		7			13	7	4	21	9	8	7	26	9	15	8		17	3	8	
incertum									7					10	1	7		2			1		1		5							3			9		.6	2			6	2	
matagordanum															1				1												3		2			3		1					
poeyanum									3				6	3					.2	.5											1												
translucens																														1	.7	3	1	1		.4					3		
tumidum																			.2											.2	1												
ides hannai															.3																	1				.4				17			
ryina exilis										.4					.3		.7		.4	.5		2	1	11				2	1			1	.5	1		1	4						33
ulina australis		4	3	3		6	2	1	1				3	1	.6		.7		.2	.5		2	1	11				2	1			1	.5	1		1	4						33
lidae		3	10	61		11		15	25	13	33		6	30	9	27	13	24	6	2		15	24	33	21			17	13	5	4	3	4	18		16		5	75		6		67
onella atlantica		2	6				2	4	1	9	3				8	20	6	4	8	13	8	2	6	11	2			2	15	26	16	1	17	14		8	12	12			3	9	
opima								1		1			3		1	1			.4		1		1		1			1	1	2	1		1	1			1	4			3		
eonina lagenaria																												1	1									.7			3	1	
sp A																																		.4		.2							
sella atlantica							.4	.6																									.3					.7					
lia" beccarii vars.		30	29	9		13	21	10	11	33	22		12	12	36	20	36	13	48	48	80	5	12	33	23			17	35	46	34	40	38	21	36	30	22	35			33	29	
rolshauseni									3						.3				1										1	.7	1		.3					1					
ularia cf. mayori				4																			1					1										.7					
ulina pontoni															.3	.5	.4		.7										1	.5	.3			1		.2	.6					1	
LANKTONIC FORAMINIFERA																																											
igerina bulloides								40	30																					10													
gerinoides rubra						30	60	160		200					30		60		100		4		30							40	30	60		30			60	30			15		
entified globigerinids							60																											30									
strocoda		130	30	100		60		600	200	600	60			200	1000	1000	1000	130	900	180	10	200	200	30	260			600	540	48	320	380	1000	1000			5400	5000			80	600	
atoms																																											
inodiscus		R	R		R		R		R	C	R	A	R		C	C	A		R	R	C	R	R		R	R			A	A	R	R	A	R	R	A		R		R	R	C	R
sira									R		R	R			R					R	R	R	R						R				R									R	
rcitium											R				R			R		R	R					R					R	R									R	R	
cal pellets		C			R		R		R			A	R		R	R	C	R	A	C	A	R	R	R	R			R	A	A	C	C	A	A		A		R			A	A	R

Table X. Occurrences of Foraminifera, et cetera, in Open Gulf. Foraminifera in Percentage of Total Population.

	OPEN GULF																																													
STATION	1247	1248	1249	1250	1251	1252	1253	1254	1255	1256	1257	1260	1261	1262	1263	1264	1266	1267	1268	1269	1270	1271	1378	1379	1380	1381	1382	1383	1384	1386	1388	1391	1392	1393	1394	1395	1396	1397	1398	1399	1400	1401	1332	1333	1336	1337	1338
TOTAL POPULATION	160	9000	6,000	1,900	2,200	1,100	100	4,100	9,600	2,400	1,000	500	500	9900	>10,000	>10,000	>10,000	1,200	2,900	2,000	1,200	3,700	60	60	7,000	840	3,900	3,800	1,300	220	>10,000	60	5,900	550	>10,000	>10,000	9,100	1,300	3,700	4,500	1,800	3,600	50	4,900	>10,000	1,900	230
BENTHONIC FORAMINIFERA																																														
Ammobaculites dilatatus															2	2																	.6		.5	1	1	.6		.4		16				
A. exiguus		.3					33																																							8		.2		
A. exilis		1						.5																																								
A. salsus	100		.5		2			1		3						.3	.4			1													3	86			1			1		1			16	1		2	
A. sp.				3		3		1	1					.6				4		2		2			1		2									15	1	1		4	.2	1	2	1	38	.3	1		
Asterigerina carinata					2			1	.3	3			12					1		1	3						1	2			1			7	3	1	2				.5	2			.2		
Bigenerina irregularis		3	3	3	2		33	6	4	4		13		4	4	10	5		10	4		9			3	13	6	2			12			7	4	8	1			2	1	2		1	1	3	14
Bolivina lowmani		.6	1					.5							.6	2	1	2	6	3			2			1	4							.6		.5	1		.6	1		2			1	.4		
B. pulchella var. primitiva																	.3	.4															1					.5	.3					1		.3			
B. striatula var. spinata								.5																												.3									.3	.2		
Buliminella cf. bassendorfensis		1						1	.3						1	.6	2	4	1						1									2		1				.5	1	2			8	2		
B. elegantissima		1	1		2			1	.3					.3	1		2	15	4	1					1						.2		1		.3	.5		8	1	2	2			2	3		
Cibicidina strattoni		17	8	17	18	34		23	16	35	34	38	18	21	15	14	7	3	22	30	46	27		100	16	40	51	43	45	14	23		5	7	11	10	34	.6		3	4	24		2	4	12	
Discorbis cf. columbiensis		6	6	2	2	3		6	6		3			5	5	3	1	3	5	8	5	11			11	2	2	5			7	14	20	7	15	18	14	2		12	10	20		5	5	2	
D. floridana		.6	.5	2	2	3						6		2		.6	1			2					1		1				1		3	7	1	.5	.3	.6		2	2	3		.3	.2		
Elphidium advenum		.6			2				.3		9		6	.3			.4		2								2			.2				.3	1						.4			.2		
E. discoidale		2	.5	2	2	12		3	.3	4	3	6	12	3	.4	2			4	4	3	11			2	2	6	2	3						2	3	1			1	2	2		.3	1		
E. galvestonensis																	1	1																												
E. gunteri		13	6		2	3			12	12	7		6	24	.4	2	.4				8	1					8	5	9		.2		5			.5	1			7	2	5		3	20	13	
E. incertum			2	9	8	12		6	1	7	10	6		2	14	12	2	7	12	6	8				5			4	3		1		2		3	7		4	2	1	7			18	1	12	
E. koeboeense													6				1																.3								1					
E. matagordanum			1					1									1																2				.3							.4		
E. poeyanum		.6		5	2			8					6	.3	2	3	2		1			3			1			1										1			1		3	.4		3	.4		
E. translucens		1					33		3	3				2			.4									1											.6						2			4		
E. tumidum		2													.4	2	3			1		1															1		3	.2		.5				.3		2	
E. sp.		.6		9	15	3		7	1	3	3			.3		3		11		1		6			3					14	1		.3	15	3	3	4	1	4	1	7	.4		1	5	3	14
Eponides hannai		.3	.5							1																					.2						.3										
Gaudryina exilis								.5						6			.3		1							1			1						.9						.5	.4		.4				3	14
Guttulina australis		.6		1				2		9	14	6		1		1	.4				1				1		1	2			1			7	.5	2	1										
Miliammina fusca																											2	1																				
Miliolidae		9	26	7	7	6		7	21	17		13		9	12	7	4		16	8	3	7			8	33	10	20	10	14	28		11		23	3	25			13	9	14		5	3	8	55
Nonionella atlantica		10	12	17	7			6	9	1	3			6	13	13	33	3	4	4	3	6			7		2	2	3		8		5		7	11	4	7	8	7	9	4		5	11	7	
N. opima		.3	2		2			1	1							2	1									1						.4		.3		.3					2	4	.4		2	2		
Proteonina atlantica																														1			.2																
P. lagenaria															.6		.3		4														14	.2				.3		.6										
P. sp A																				1																													16				
Reophax																					3												14				7				.6	.2				8	.3			
Reussella atlantica		.3	.5												.3							3							1			1						.3						.4			2		
"Rotalia" beccarii vars.		25	30	25	30	21		16	22	15	6	13	35	16	25	20	26	34	11	22	16	12	100		32	4	6	4	5	29	8		40		19	24	10	58	80	41	29	14		41	36	33	
"R." rolshauseni		.6	1						.3	1	3			.3	.4		2																	.3							1							
Textularia cf. mayori			.5														.4									1						1				1		.3						.4					
Trochammina laevigata																																			7	.5												
Virgulina pontoni									.3					.3			1	1	2						1			1			.4		.6		.5	1		1		1	.5				.4		
Planktonic Foraminifera																																														
Globigerina bulloides																																													60		
Globigerinoides rubra		30			30			30							60	130	200		30		60	30			25			60	30		100		15		130	260			8		8	30		120			
Orbulina universa																																				60										
unidentified globigerinids		30																									30																					120			
Ostracoda		580	780	350	160	60		740	1100	200	30		30	1200	[illegible]	3000	[illegible]		[illegible]	100	200	200			560	15	160	400	100		[illegible]		350	30	[illegible]	[illegible]	1100	120	60	430	80	400		140	[illegible]	160	
Diatoms																																														
Coscinodiscus	R	R	R		R	R	R	R	R		R			R	R	C	R	A	R	R			C	R	C	R	R	R	R	R	A	A	C	R	R	R	R	A	C	C	A	R	A	A	R		
Melosira		R	R														R		R		R					R						R	R	R	R	R			R	R	R		R		R			
Triceratium			R			R												R					R		R			R			R	C	R		R	R		R	R	R	R			R			
Fecal pellets	R		R					R	R						R	R		C	A	R	R			R	R	R		R		R	R	R	A	A		R	R	R	A	A	A	A		A	R	R		

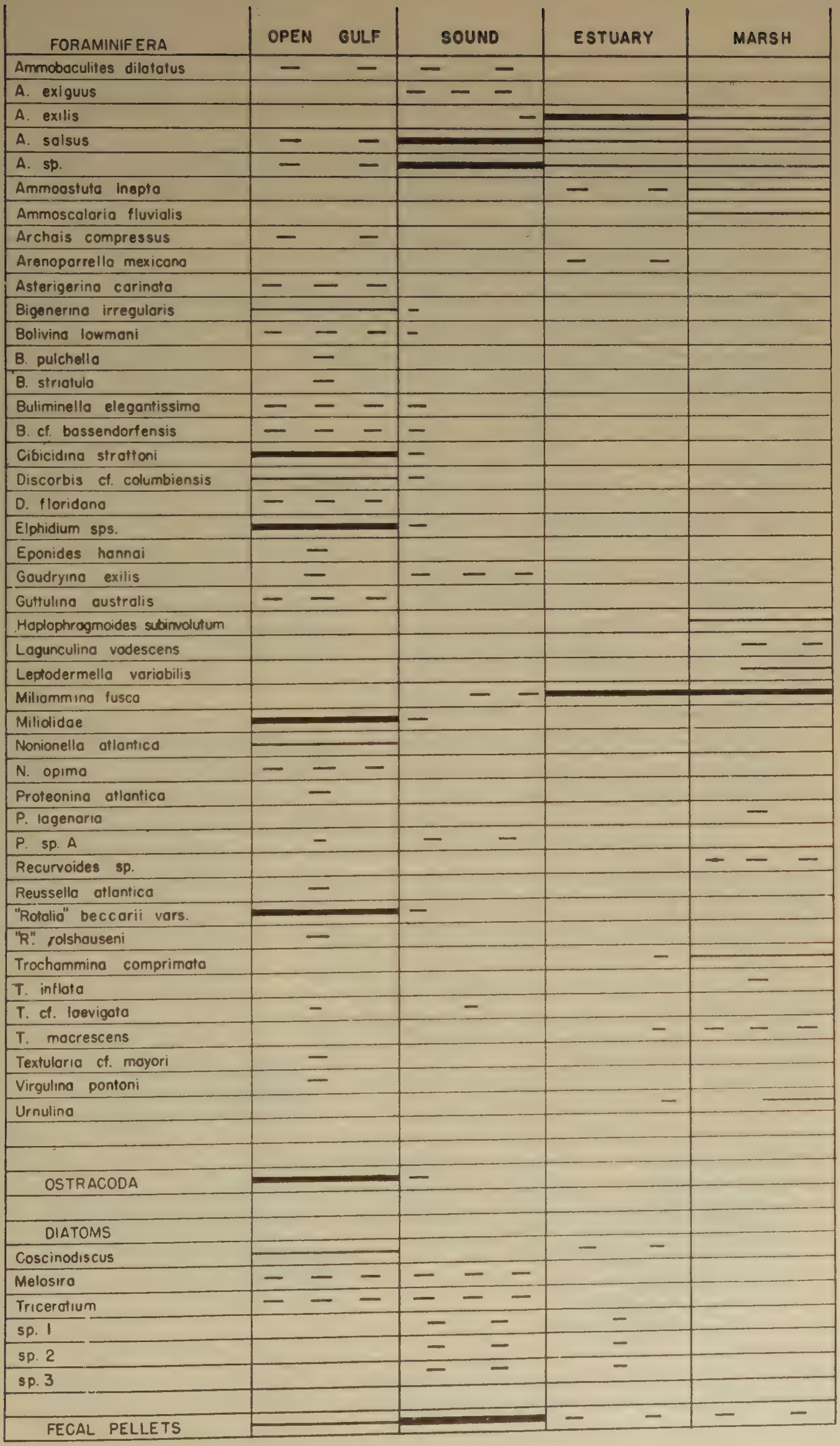


FIG. 4.—Generalized facies ranges of species.

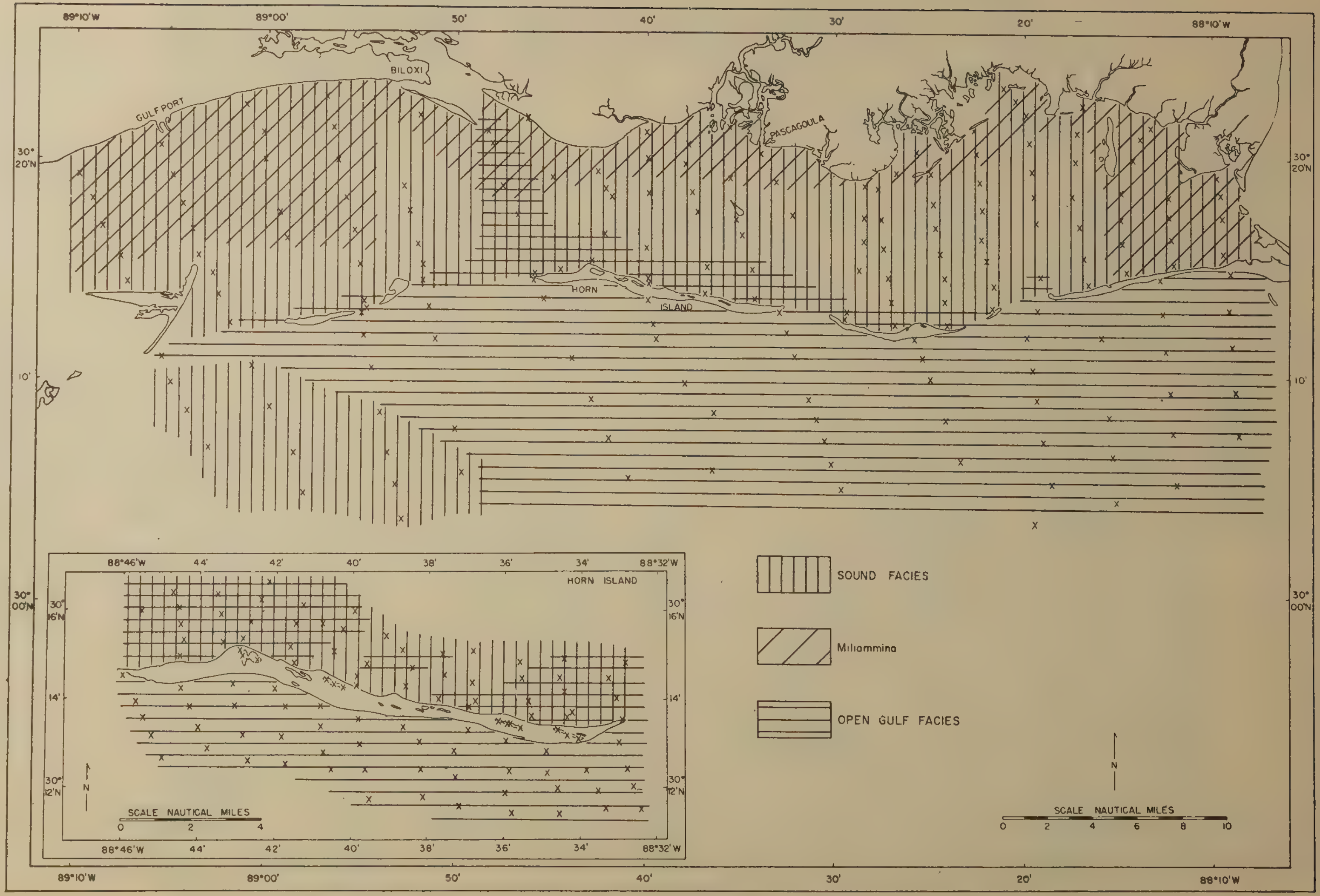

89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
BILOXI
GULF PORT
PASCAGOULA
HORN
ISLAND
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
HORN ISLAND
30° 16'N
14'
30° 12'N
N
SCALE NAUTICAL MILES
0
2
4
SOUND FACIES
Miliammina
OPEN GULF FACIES
SCALE NAUTICAL MILES
0
2
4
6
8
10

FIG. 5.—Geographic distribution of facies in Mississippi Sound and adjacent open gulf.

with those reported by Phleger (1951) from the upper part of the continental shelf between Atchafalaya Bay, Louisiana, and Pt. Isabel, Texas.

SOUND FACIES

The sound facies occurs in Mississippi Sound and at the westernmost open-gulf stations north of the Chandeleur Islands and south of Ship Island. This fauna is quite different from the open-gulf fauna, being composed exclusively of arenaceous species. It is made up almost entirely of two or more species of *Ammobaculites*, principally *A. salsus*. The following species are characteristic of the sound facies.

Ammobaculites exiguus
A. salsus
A. sp. (probably mostly *A. salsus*)

Gaudryina exilis is more common in the sound facies than elsewhere, but also occurs in the open-gulf facies.

Several open-gulf species occur near inlets and at other places. *Miliammina* is present in the sound facies near marshes and streams.

Coscinodiscus diatom species 1, 2, and 3 and fecal pellets seem to be more abundant in Mississippi Sound than elsewhere in the area.

ESTUARY FACIES

The estuary facies is characterized by *Ammobaculites exilis* and *Ammoscalaria fluvialis* which are more abundant in this environment than elsewhere. *Milliammina fusca* also is abundant and these three species dominate the fauna. *M. fusca* also is abundant in the marsh. In addition several of the marsh species occur in the estuaries but they are in lower frequencies than in the near-by marsh. The estuary and marsh facies are closely interrelated and probably should be combined into a single facies. They are given facies rank here, however, for simplicity and to emphasize that usually they can be differentiated in this area.

MARSH FACIES

The marsh fauna can be differentiated by the abundance of the following.

Ammoastuta inepta
Arenoparrella mexicana
Haplophragmoides subinvolutum
Leptodermella variabilis
Recurvoides
Trochammina comprimata
T. inflata
T. macrescens
Urnulina

Most of these species also occur in the estuaries but in significantly lower frequencies, and such occurrences are interpreted as contamination from the marsh. *Miliammina fusca* is abundant but also is abundant in the estuaries. Other species which occur in significant frequencies in some places but also occur in other environments are the following.

Ammobaculites exilis
A. salsus
A. sp.
Ammoscalaria fluvialis

Leptodermella variabilis and *Urnulina* appear to be characteristic of the inner marsh areas where they may constitute the bulk of the population.

BIOFACIES BOUNDARIES

The boundaries between biofacies show varying degrees of intergradation and/or mixing between facies. The spacing of samples over most of the area does not permit a detailed study of boundary features but it is believed that at least the major features are shown.

The boundary between the open-gulf facies and the sound facies appears to be the sharpest of any studied in the area and in general follows the seaward sides of the barrier islands. The open-gulf assemblage extends into the sound, however, at the positions of inlets; this is most marked landward from Dog Keys Pass and Horn Island Pass. The extension of the open-gulf fauna into the sound at the position of Petit Bois Pass is less marked. The open-gulf fauna extends almost to the mouth of Biloxi Bay north of Dog Keys Pass. North of Horn Island Pass this fauna extends only about halfway to Round Island approximately 2 miles and for about the same distance north of Petit Bois Pass.

Specimens of the offshore fauna also occur on the Mississippi Sound side of Horn Island and Petit Bois Island. These distributions are better known behind Horn Island where there is a closely spaced grid of stations. Here the open-gulf species occur at numerous stations for a distance of 1–2 miles behind the island with more frequent distributions toward the inlets at either end. Many samples on the sound side of these two islands are characterized by having very low populations and having a high percentage or being composed entirely of such offshore forms as *Elphidium* and/or "*Rotalia*" *beccarii* vars. Many of the samples taken nearest the island shores on the seaward side also contain very low populations. Several beach samples examined contain few or no specimens; specimens present are commonly of larger open-gulf species and show evidence of erosion.

Thirteen samples were collected from the small ponds on Horn Island. Ten of these samples contain relatively small populations. Seven of the samples contain an assemblage typical of the estuaries on the mainland with high frequencies of *Ammobaculites exilis* and *Miliammina fusca* at two stations and of *Ammoscalaria fluvialis* at two other stations. *Leptodermella variabilis* and *Urnulina*, typical marsh forms, occur at one of these stations containing an estuarine assemblage, and *Trochammina inflata* occurs at another station. Three of the stations contain a rather typical Mississippi Sound assemblage. Open-gulf forms are found at two stations: at station 1170 the fauna is a pure open-gulf assemblage and at 1173 it is a mixed sound and open-gulf fauna. It may be of interest that open-gulf species have been found only in the ponds on the western half of Horn Island.

Open-gulf species extend westward as far as the station nearest the southern tip of Cat Island and the southern boundary of this fauna extends east and a little south from this point. South of this line extending to the northern-most end of Chandeleur Sound the fauna is that of the sound facies.

Miliammina fusca is a species which is very abundant in most marsh and estuary samples occurring in frequencies which average 50% or more of the populations. *M. fusca* is widespread in Mississippi Sound at stations fringing the mainland for distances up to 3–4 miles. The frequencies in these samples generally are much lower than in marsh and estuary samples, 1–10 per cent, except at stations off Graveline Bayou and the Pascagoula River where abundances are similar to those in the estuaries which drain into these areas. *M. fusca* is present in low frequencies at all stations in the eastern end of Mississippi Sound, east of a line running northerly from about the middle of Dauphin Island.

The boundaries between the marsh and estuary facies are not sharp because of the relatively intimate association of the two environments. Species which are characteristic of the marsh commonly occur in much lower frequencies in nearby estuary samples. In the upper reaches of small estuaries where they are very narrow, marsh Foraminifera may occur in both environments in comparable frequencies.

ECOLOGIC AND OCEANOGRAPHIC DISCUSSION

ECOLOGIC FACTORS

The principle feature of the facies distribution is the marked contrast between the open-gulf facies and the sound facies. The open-gulf population is 90% or more calcareous species, and the sound fauna is entirely arenaceous, except where offshore elements have been introduced. The boundary between these two assemblages is marked.

It is not possible at this stage of our knowledge to indicate which specific ecologic factors are of primary importance in causing the discontinuous distributions of different species of Foraminifera. It is apparent that all of the following features of the marine environment are of possible importance in varying degrees in different environments: temperature, salinity, food supply, turbidity, nature of the substrate, depth, turbulence, biological competition, chemistry of the water, *et cetera*. It is possible that other, unknown factors also affect these distributions. It may not be possible to determine the relative importance of these factors without physiological experimentation under controlled conditions. This is a laborious and not entirely satisfactory procedure and there is no assurance that results obtained on one species will apply to any other species. It may not be necessary to obtain specific information on the effects of each environmental factor for oceanographic and geologic interpretations of facies distributions. Much can be learned by analysis of actual distributions in the present ocean.

WATER MASS DISTRIBUTIONS AND CONSEQUENT FAUNA

Physical oceanographers recognize different "water masses" on the basis of their salinity and temperature characteristics. The concept, or at least the term, of water masses may be modified for ecologic purposes to include all the physical, chemical, and biological features of any body of marine water which seem to have a uniform ecologic effect. Many of the characteristics of such a water mass may not be known except in general terms; something frequently is known about temperature and salinity distributions. Data now accumulated indicate that populations of both planktonic and benthonic Foraminifera may be used to delineate certain of these water masses and to trace their movements. This concept can be applied to interpreting distributions in the present nearshore area and in comparing them with those found in other nearshore areas.

The presence of the barrier islands and the high runoff from the land are suggested as the basic factors causing the discontinuous distributions of benthonic Foraminifera found in the Mississippi Sound area. The islands act as an effective barrier in preventing invasion of the open-gulf water mass along a wide front. The presence of planktonic Foraminifera only in very low frequencies in the present open-gulf fauna suggests that the open-gulf water mass affecting these present populations is the one characteristic of the inner part of the continental shelf. A considerable amount of fresh water empties into Mississippi Sound, particularly from the Pascagoula River. This runoff tends to keep the sound full of water and aids in inhibiting inflow of the open-gulf water mass through the inlets between the islands.

Open-gulf water undoubtedly invades the sound through the inlets mainly by creep along the bottom. Under certain circumstances, such as on the flood tide and/or times of low runoff, undiluted gulf water may fill the entire cross section of the inlets. This water of relatively high salinity is mixed soon with the fresh runoff water by wave action in the shoal depths of the sound. A water mass of lower-than-open-gulf salinity thus is formed in Mississippi Sound. This sound water flows out through the inlets generally at the surface because of its lower density and eventually it is mixed with open-gulf water.

Distributions of the open-gulf benthonic Foraminifera in the sound clearly reflect the routes of invasion of the gulf-water mass. It is believed that these distributions reflect the average conditions over a period of time. A survey of the water characteristics at any particular time, on the other hand, can indicate only conditions obtaining at the time the survey was made. Since the species used are all benthonic, they probably reflect principally the environmental characteristics of the water near the bottom. The distributions suggest an average invasion of unmixed gulf water along the bottom of approximately 2 miles inside the inlets. An exception is noted in the traverse of samples extending north of Dog Keys Pass at the western end of Horn Island. The distributions here suggest at least occasional invasions almost to the shore of the mainland. The fact that unmixed gulf water does not invade Horn Island Pass at the eastern end of Horn Island for a greater distance may be due to the outflow of runoff from the Pascagoula River in this area. The presence of open-gulf species behind the islands suggests

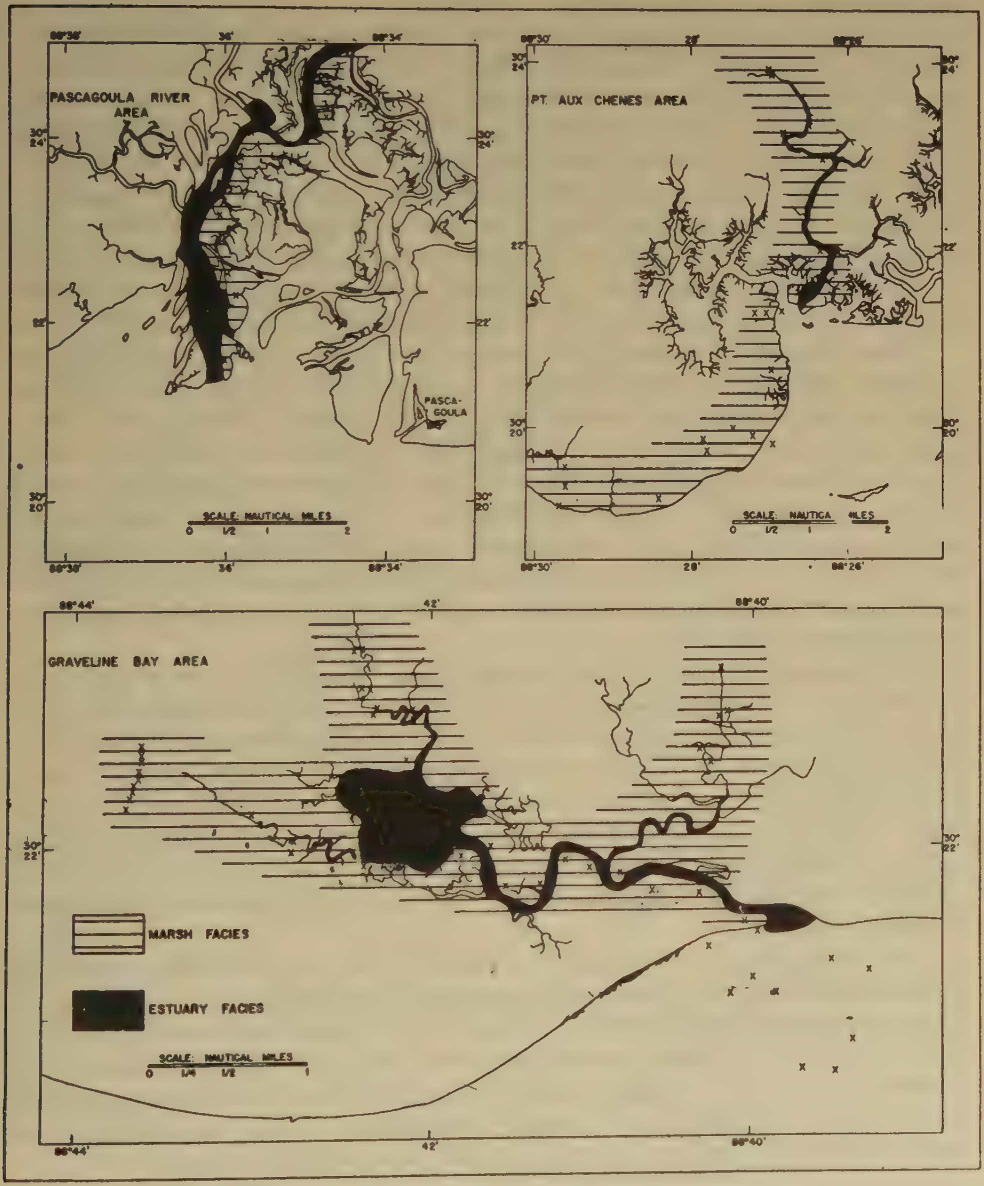

PASCAGOULA RIVER AREA
PASCA-GOULA
PT. AUX CHENES AREA
GRAVELINE BAY AREA
MARSH FACIES
ESTUARY FACIES
SCALE: NAUTICAL MILES
0 1/2 1 2
0 1/4 1/2 1
88°38'
36'
88°34'
88°30'
28'
88°26'
88°44'
42'
88°40'
30° 24'
22'
30° 20'
30° 22'

Fig. 6.—Geographic distribution of facies in marsh and estuaries.

that the invading water spreads laterally into these areas and becomes mixed along a broad and irregular front.

The Foraminifera distributions in the western part of the open-gulf area, between the northern end of the Chandeleur Islands and Ship Island, are of considerable interest. In this area the average condition, based upon the microfauna distributions, seems to be approximately as follows. The open-gulf water extends in a tongue, probably along the bottom, only in the northern part of this wide inlet, along the southern side of Ship Island and as far as the southern point on Cat Island. The southern part of the inlet, essentially open gulf in the geographic sense, contains a sound fauna (Fig. 6). This appears to reflect a very large outflow of relatively fresh, sound-type water which probably originates in Chandeleur Sound and from the upper part of the older Mississippi Delta area.

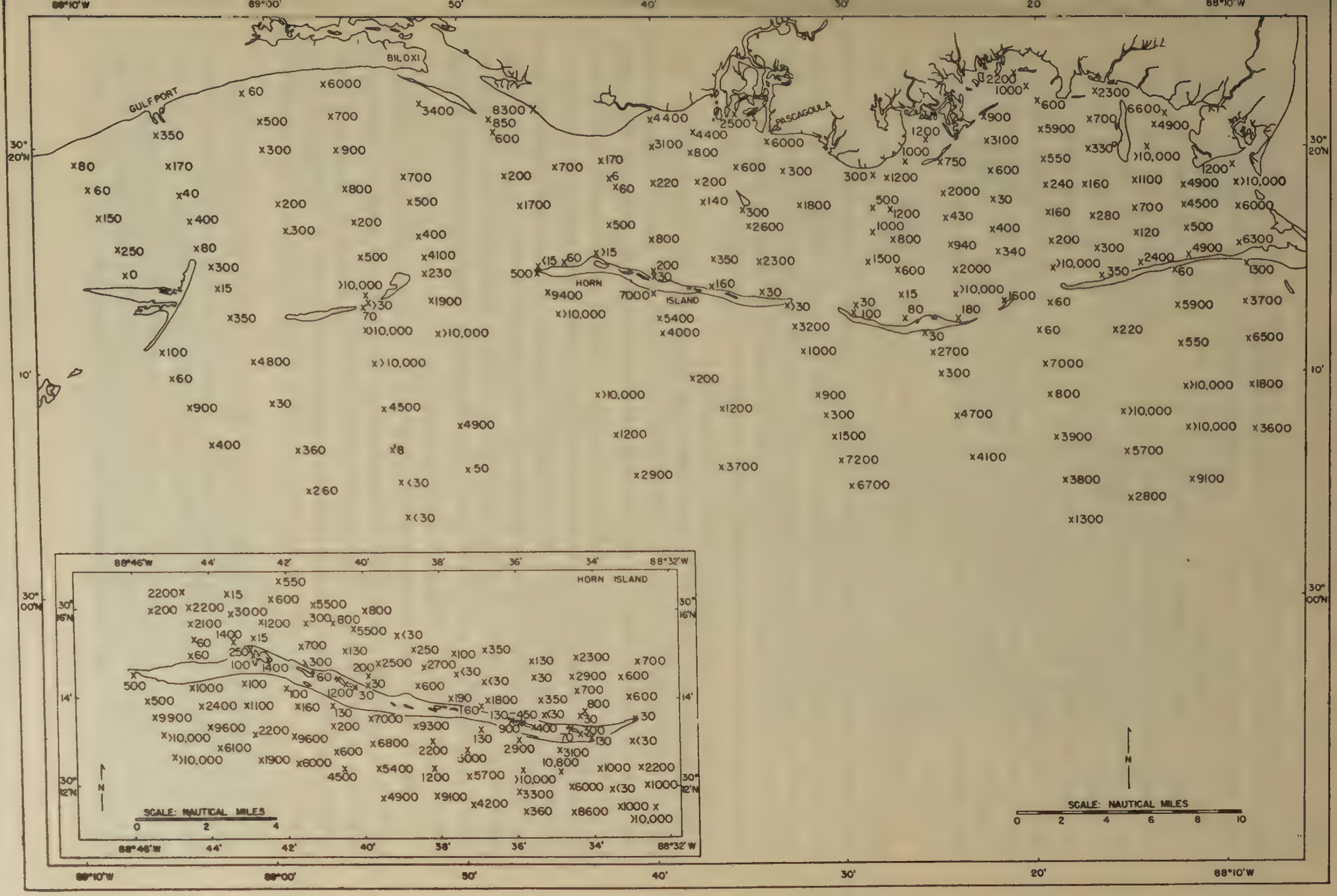
It is of interest to observe that there is less mixing of sound species on the outside of inlets than of open-gulf species on the inside of the same inlets. This is based on the comparative frequencies of the two groups of species where they occur in foreign locations. This provides a clue for determining whether a mixed fauna occurs on the outside or the inside of inlets. This situation may be explained by the fact that these are benthonic organisms. Since most of the sound water escaping into the open gulf rides over the gulf water because of lower salinity and density, the benthonic assemblage is not generally carried with it. The gulf water invades along the bottom, however, and the open-gulf species are easily introduced into the sound.

The question naturally arises whether these "displaced" species are introduced because of ecological features of the water mass which they inhabit or whether they are transported by currents. The writer is aware of no certain way to resolve this problem without a detailed study of bottom currents in this area, along with laboratory experiments on the transportation of the tests. It may be argued that the distribution of living specimens would provide the clue, but this is not necessarily true. Living Foraminifera appear to be transported as easily as empty tests, in the experience of the writer in dealing with fluid samples in counting trays.

The faunal difference between the estuaries and the surrounding marsh is surprising since these two environments seem to be so closely associated and to form a geographic unit. The intimate association is shown by the abundance of *Miliammina fusca* in both environments. The distinction lies in the restriction of certain species to the marsh. This is obviously a quieter environment than in the streams, the salinities are probably somewhat different, and marsh plant assemblages undoubtedly have a marked influence on the microfaunas.

COMPARISON WITH OTHER AREAS

Two other areas in the northern Gulf of Mexico have been studied which show distribution patterns similar to those found in the Mississippi Sound area. One of these areas is northeast of Corpus Christi, Texas, centering around San An-



GULFPORT
BILOXI
PASCAGOULA
HORN
ISLAND
HORN ISLAND
88°10'W
89°00'
50'
40'
30'
20
20'
10'
30° 20'N
30° 00'N
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
N
SCALE: NAUTICAL MILES
0
2
4
6
8
10

Fig. 7.—Total populations of Foraminifera in Mississippi Sound and adjacent open-gulf samples. Uniform size samples.

tonio Bay, reported by Parker, Phleger, and Peirson (1953). In the San Antonio Bay area there are an open-gulf population and a bay population; most of the species are also common to the Mississippi Sound area. There is one striking difference in detail of species distribution between the two areas, however, which has important implications. *Elphidium* spp. and "*Rotalia*" *beccarii* vars., which in the Mississippi Sound area are confined to the open gulf, also are present in abundance throughout the bay environment, as well as the open gulf, in the San Antonio Bay area. The two areas are similar in having barrier sand islands separating the open gulf from the lagoon. In the San Antonio Bay area the inlets are fewer and much narrower than in the Mississippi Sound area. The presence of these two open-gulf species in the bays and in the Texas area is surprising, since the geographic barriers to invasion should be more effective than in the Mississippi area.

The explanation for these distribution differences appears to be related to the differences in rainfall in the two areas as it affects runoff from the land. The southwest Texas area is in a steppe climatic belt where the average rainfall for several years preceding our collections was less than evaporation from the drainage basin. As a result, most of the water in the bays was originally open-gulf water entering through the inlets. This source of water is demonstrated by the bay salinities which are significantly higher than open-gulf salinities, except during flood periods, ranging up to more than 40°/₀₀.

It appears that "*Rotalia*" *beccarii* vars. and *Elphidium* spp. migrated into the bays with the open-gulf water mass, found the environment suitable, and become one of the dominant elements of the bay microfauna. These species groups seem to be able to withstand considerable ranges in salinity and perhaps in other ecologic factors as well. It appears, however, that their basic ecologic adjustment is to the open-gulf water mass. Other open-gulf species also are in the bays in the San Antonio area but they are confined to the lowermost bays and mostly are present near the inlets. The bay microfauna in this area can be differentiated from the open-gulf fauna by the abundance of the same species of *Ammobaculites* which characterize the Mississippi Sound fauna.

These interpretations of the faunal patterns in the two areas suggest criteria for indicating relative runoff from such areas. Further, the type of climate is indicated for the drainage basins which constitute the source of supply of sediment being deposited in the marine area being considered. Such information may have important implications as more understanding of sedimentary processes in marine areas is obtained.

It is interesting to speculate upon the faunal patterns which might exist in the Mississippi Sound area under arid or semi-arid climatic conditions in the drainage basin. Under such conditions it is expected that the flow of open-gulf water into and out of Mississippi Sound would be much less restricted than in the San Antonio Bay area because of wider and more numerous inlets. With unrestricted flow in both directions and with little or no runoff, the sound would be

Table XI. Occurrences of Foraminifera off Atchafalaya Bay, in Percentage of Total Population.

SAMPLE	1	2	3	4	5	6	7	8	9	10	11	12	13
DEPTH IN FEET	7	8	10	9	8	8	9	10	10	7	8	9	9
TOTAL POPULATION	23,800	4,600	8,300	6,800	9,900	1,500	7,200	1,100	10,800	4,300	500	2,900	6,200
SPECIES													
Ammoastuta inepta		1			.6	2	.2		.3	1		.3	.3
Ammobaculites salsus	44	46	40	66	57	35	72	24	18	40	17	20	23
Arenoparrella mexicana		1	1	1	.6	1	.2			1	.4		.3
Bolivina lowmani								.7	.3		.4		
Buliminella cf. bassendorfensis								1	.3		.4	.3	
Elphidium discoidale	32	20	25	6	5	18	2	21	15	15	16	12	6
E. gunteri	.5	2	2			2		.7	1	1	2	.3	.3
E. incertum mexicanum	2	2	1		.6	1						.3	
Leptodermella												.3	
Miliammina fusca	9	11	12	15	21	11	21	3	3	.4	1	2	.5
Miliolidae								4		.4	.4		
Nonionella atlantica											.8		
"Rotalia" beccarii vars.	13	17	18	12	14	30	4	45	61	41	61	65	66
Trochammina macrescens		.3										.3	
Urnulina			.4		6								

filled with an unmodified open-gulf water mass. All elements of the open-gulf fauna would be expected to be in all parts of the sound. Whether or not the *Ammobaculites* fauna of the sound were present would probably depend on the degree of aridity.

The fauna where no barrier island is present in a nearshore marine area of high runoff is shown for a traverse off Atchafalaya Bay (Table XI). A traverse containing 13 surface core samples extending approximately 12 miles offshore from Pt. Chevreuil was collected by Warren Thompson for the writer. This area differs from the Mississippi Sound area in at least three important respects.

1. There are no barrier islands. There is thus no geographic barrier to the invasion of open-gulf water masses.
2. The continental shelf is very wide with a gentle seaward slope, and there are numerous small shell reefs.
3. There is a mud-marsh shoreline directly open to attack by open-gulf waves.

In this area the single traverse of samples contains the *Ammobaculites-Elphidium-Rotalia* fauna which is similar to that in the bays in the San Antonio Bay area and, in addition, marsh-estuary species are present in all samples, extending approximately 12 miles offshore.

This faunal pattern may be characteristic of areas near the mouths of large rivers which carry a big load of sediment. In such a situation probably there are marked and large-scale fluctuations in the character of the water mass at any nearshore location. At certain times, especially during flood stages and low wind velocities at sea, the almost fresh-water mass from the estuary might cover a large nearshore area. Under conditions such as low runoff or shift in wind velocity or direction, an almost pure open-gulf water mass would be present. At other times a mixed water mass similar to that in Mississippi Sound might occur, such as during heavy winds which cause considerable mixing.

The writer is aware of only one apparent criterion for differentiating an environment such as in Atchafalaya Bay with no barrier island from the one like San Antonio Bay with a barrier island. There is a relative abundance of marsh and estuary species in the Atchafalaya Bay samples and these are very rare in the San Antonio Bay samples. This reflects the presence of extensive marsh in the basin draining into Atchafalaya Bay, and also the presence of a large river and/or unrestricted wave action directly on the marshy shoreline. The marsh forms are *Miliammina fusca*, *Leptodermella*, *Urnulina*, and various species of *Trochammina*. In general, there appears to be a decrease in abundance of marsh and/or estuary forms in an offshore direction.

DISCUSSION OF GEOLOGICAL APPLICATIONS

Applications of these data and suggested principles of distribution to middle and late Tertiary marine sediments are not expected to be complicated by significant differences in species composition. In early Tertiary sediments species assemblages closely related to those found in these environments should facilitate facies definition. The problem of comparison of Cretaceous faunas with modern facies would certainly be more difficult and comparison may be possible only in a general way. It should be possible to apply certain general principles of distribution which are at least partly defined by the work on this and related projects.

It is necessary to analyze a fauna with care and in detail to obtain the maximum information, and this should be done from an ecologic as well as stratigraphic point of view. Most faunal analysis probably should be quantitative for maximum results. This will be difficult or impossible where there has been extensive destruction of the Foraminifera tests after deposition. Very little is known about test destruction, but in the limited experience of the writer it may be selective so that some species are completely destroyed and others are relatively unaffected. Fragments commonly are present which should be identifiable with sufficient knowledge of wall structure. Whether whole tests or fragments are preserved from such a fauna, it should be possible to estimate the entire fauna originally present. This can be done only if there is detailed knowledge of the faunal associations, and then only if certain key species are indicated.

In the opinion of the writer it is desirable to attempt to reconstruct the ancient oceanography of any marine area as background for predicting sedimentary patterns. Reconstruction of the paleoceanography can be done in a general way for certain nearshore areas such as the ones discussed in this and the accompanying reports. It appears desirable at the present stage of our knowledge to use the concept of water masses as discussed in a previous section. The Foraminifera may be considered as "tracers" of these water masses, and as reflecting the average oceanographic conditions. If the water-mass distribution can be inferred it is then possible to infer the geography and the distribution of sedimentary processes, since these are closely interrelated. It must be emphasized that the use of Foraminifera alone can not give the entire analysis. It is necessary to understand the characteristics of sedimentary materials other than Foraminifera, probable source of supply, *et cetera*. Also, it is almost certain that other organisms having recognizable remains would show comparable ecologic distribution patterns.

It may be of interest to summarize what appear to be general principles of distribution of Foraminifera from the areas discussed in this report. These principles are of necessity somewhat generalized and tentative, pending accumulation and analysis of additional distribution data on both modern and fossil assemblages.

1. Relatively continuous barrier islands will prevent open-ocean water masses and their microfaunas from invading a sound or bay (lagoon) where runoff from the land significantly exceeds evaporation.
    a. The lagoon faunas may be dominated or composed exclusively of arenaceous types, principally *Ammobaculites*.
    b. Open-ocean faunas may be dominated by calcareous forms, but will certainly be different from typical lagoon faunas.
    c. Marsh forms such as *Miliammina* are restricted to fringes on the shoreward side of the lagoon. This is due to the lagoon acting as a catch basin for the water flowing from marshy areas and also due to restricted wave action. The fauna will be *Ammobaculites* type with a few *Miliammina*.
2. Where runoff is generally low and erratic so that evaporation exceeds precipitation much of the time, open-ocean water masses will invade lagoons behind barrier islands and will carry certain elements of the open-ocean fauna into the lagoon.
    a. The lagoon assemblage composed of arenaceous Foraminifera, principally the *Ammobaculites* type, also will contain the "foreign" elements which are expected to be principally *Elphidium* and *Rotalia* types.
    b. With climatic change to greater runoff, the open-ocean forms are expected to disappear.
    c. Few or no marsh forms are expected in the lagoon sediments because the marshes are small and runoff is insufficient. The lagoon fauna will be *Ammobaculites-Elphidium-"Rotalia" beccarii* type.
3. Along an open coast having high runoff there will be mixing of open-ocean and lagoon facies. In such an area extensive marshes are expected. The marine faunas are expected to contain marsh forms, such as the *Miliammina* type, and thus can be differentiated from the other types listed.

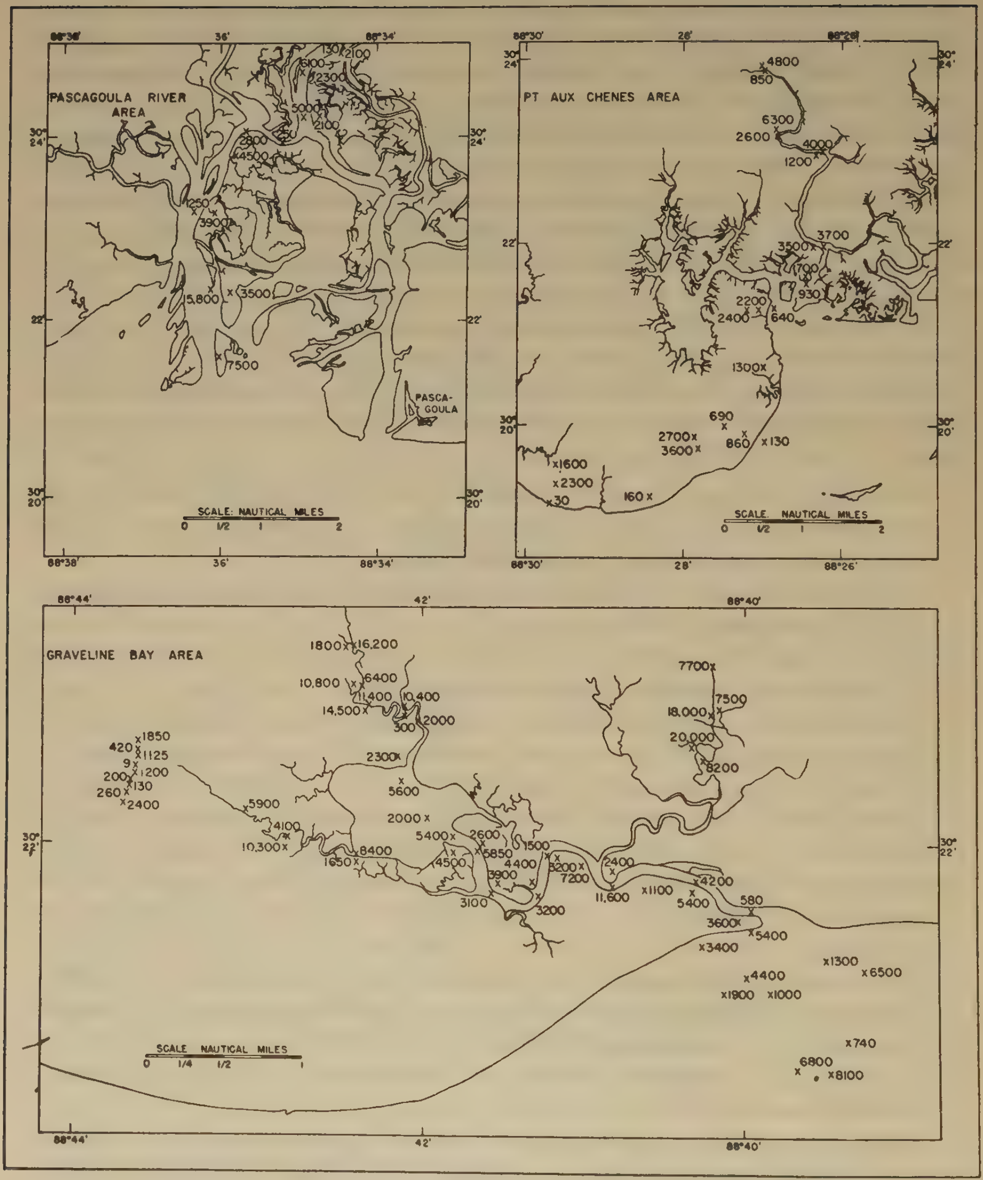

PASCAGOULA RIVER AREA
88°38'
36'
88°34'
30° 24'
22'
30° 20'
PASCA-GOULA
130
2100
6100
2300
5000
2100
250
2800
4500
250
3900
15,800
3500
7500
SCALE: NAUTICAL MILES
0
1/2
1
2
PT AUX CHENES AREA
88°30'
28'
88°26'
4800
850
6300
2600
4000
1200
3700
3500
700
930
2200
2400
640
1300
690
2700
3600
860
130
1600
2300
30
160
SCALE NAUTICAL MILES
GRAVELINE BAY AREA
88°44'
42'
88°40'
30° 22'
1800
16,200
10,800
6400
11,400
10,400
14,500
300
2000
7700
7500
18,000
20,000
8200
420
1850
1125
9
200
1200
130
260
2400
2300
5600
5900
4100
10,300
2000
5400
2600
1650
8400
4500
5850
1500
4400
3200
3900
7200
2400
11,600
1100
4200
5400
580
3100
3200
3600
5400
3400
1300
6500
4400
1900
1000
740
6800
8100
SCALE NAUTICAL MILES
0
1/4
1/2
1

FIG. 8.—Total populations of Foraminifera in marsh and estuary samples. Uniform size samples.

In analyzing and reproducing an environmental complex such as described in this report, it is of course desirable to have numerous samples with good distribution. Five or ten samples placed at random and covering the entire area should be sufficient, however, to define the environmental complex generally. This information is expected to point to locations for additional data, or may even be sufficient to make an intelligent estimate of the entire sedimentary environment and its distribution. It is believed desirable to have samples from actual exposures or well cores so that artificial faunal contamination can be avoided. Numerous important details which aid in reconstructing the patterns are based on faunal associations which are, in a sense, "natural contamination."

The problem of guide fossils is difficult in beds having ecologic patterns similar to those discussed here. An effort should be made to choose species for this purpose which occur in all environments. The best apparent potential guide species in the present assemblages, assuming limited stratigraphic range, is *Ammobaculites salsus;* this form is present in abundance in the sound facies, it is in many estuary and marsh samples in low frequency, and also in many open-gulf samples. It should be recognized in using such a form that relative abundance is of ecologic rather than stratigraphic significance. A difficulty may arise because of its absence or rarity in one or more environments, and the stratigraphic value thus may be limited. It may be more desirable to have a series of guide fossils each of which is abundant in one or more facies; their contemporaneity can be established by overlaps near facies boundaries where mixing occurs. In the Mississippi Sound area, for example, *Miliammina fusca* might be used in the marsh and estuaries, *Ammobaculites salsus* in the sound facies, and *Cibicidina strattoni* in the open gulf. Contemporaneity of these species could easily be established by their overlap distributions. The stratigraphic ranges of such forms would be established by recognized methods.

SPECIES AND THEIR DISTRIBUTION

The data on distribution of the species are listed in Tables I–XI. In addition, areal distributions of several of the more important species are shown in Figures 9–25. Frequencies less than 1 per cent are listed as 1 per cent on the distribution charts, and all other occurrences are given to the nearest whole percentage. Species in this section and illustrated on the plates are listed in alphabetical rather than taxonomic sequence.

Several of the specimens illustrated on the plates are from an area on the southeast part of the Mississippi Delta, shown in Figure 1. Distributions of Foraminifera from the Mississippi Delta area will be published in the near future and it is intended that the present illustrations of species should be used for that area. The composition of the faunas is the same in these two areas, although there are significant differences in distribution.

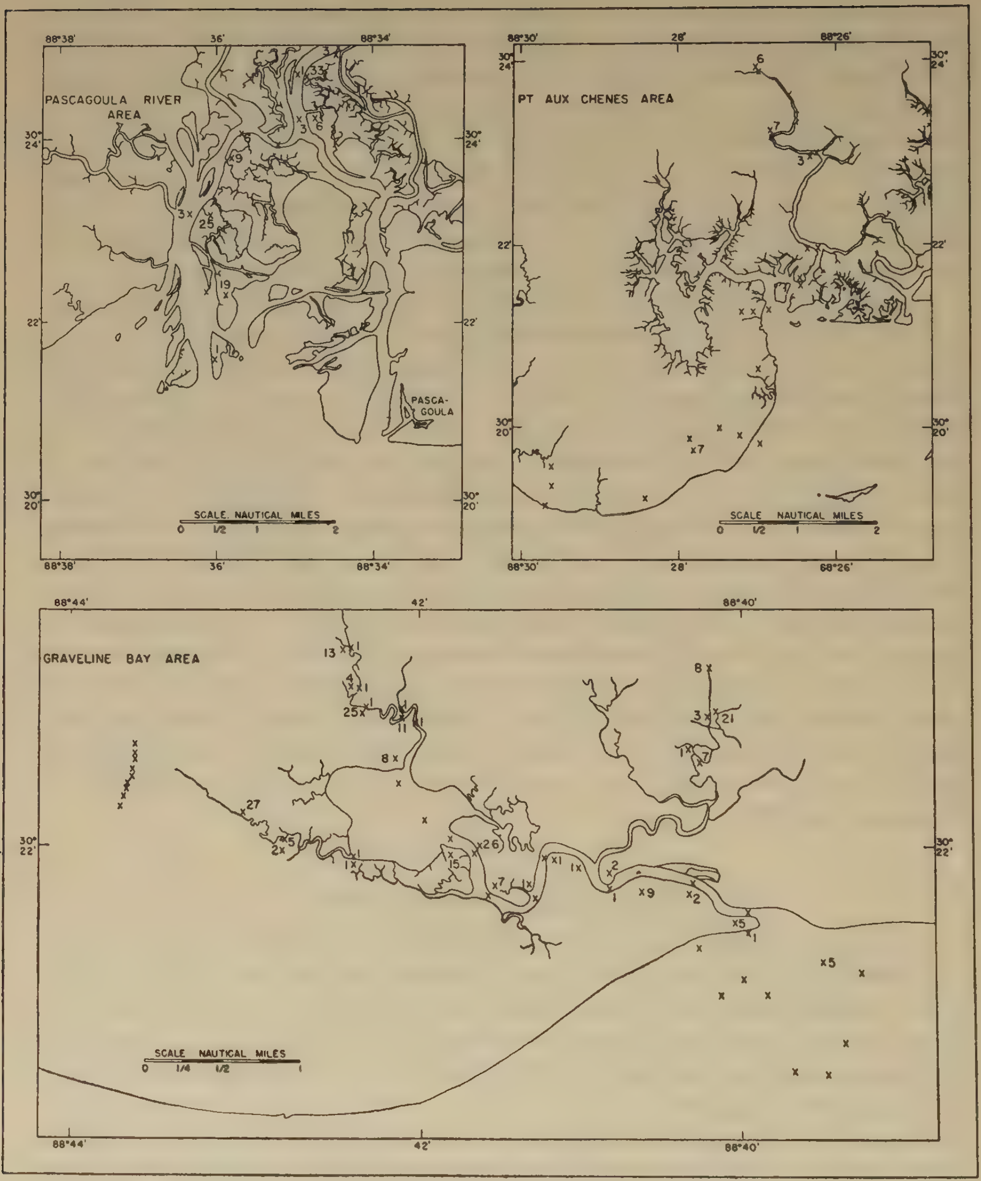

PASCAGOULA RIVER AREA
PASCAGOULA
SCALE, NAUTICAL MILES
0 1/2 1 2
88°38'
36'
88°34'
30° 24'
22'
30° 20'
PT AUX CHENES AREA
SCALE NAUTICAL MILES
0 1/2 1 2
88°30'
28'
88°26'
GRAVELINE BAY AREA
SCALE NAUTICAL MILES
0 1/4 1/2 1
88°44'
42'
88°40'
30° 22'

Fig. 9.—Distribution of *Ammoastuta inepta* (Cushman and McCulloch) in percentage of total population.

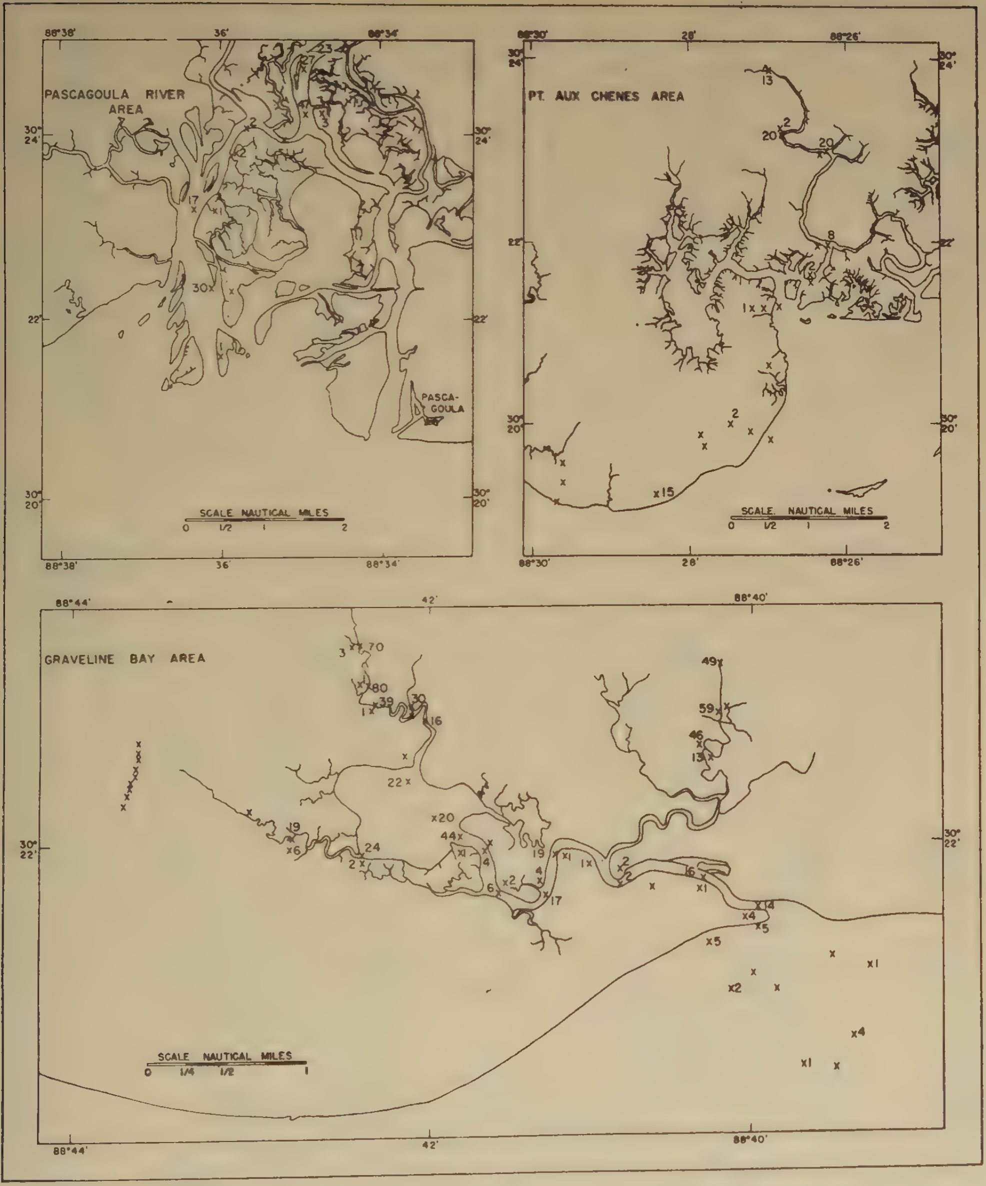
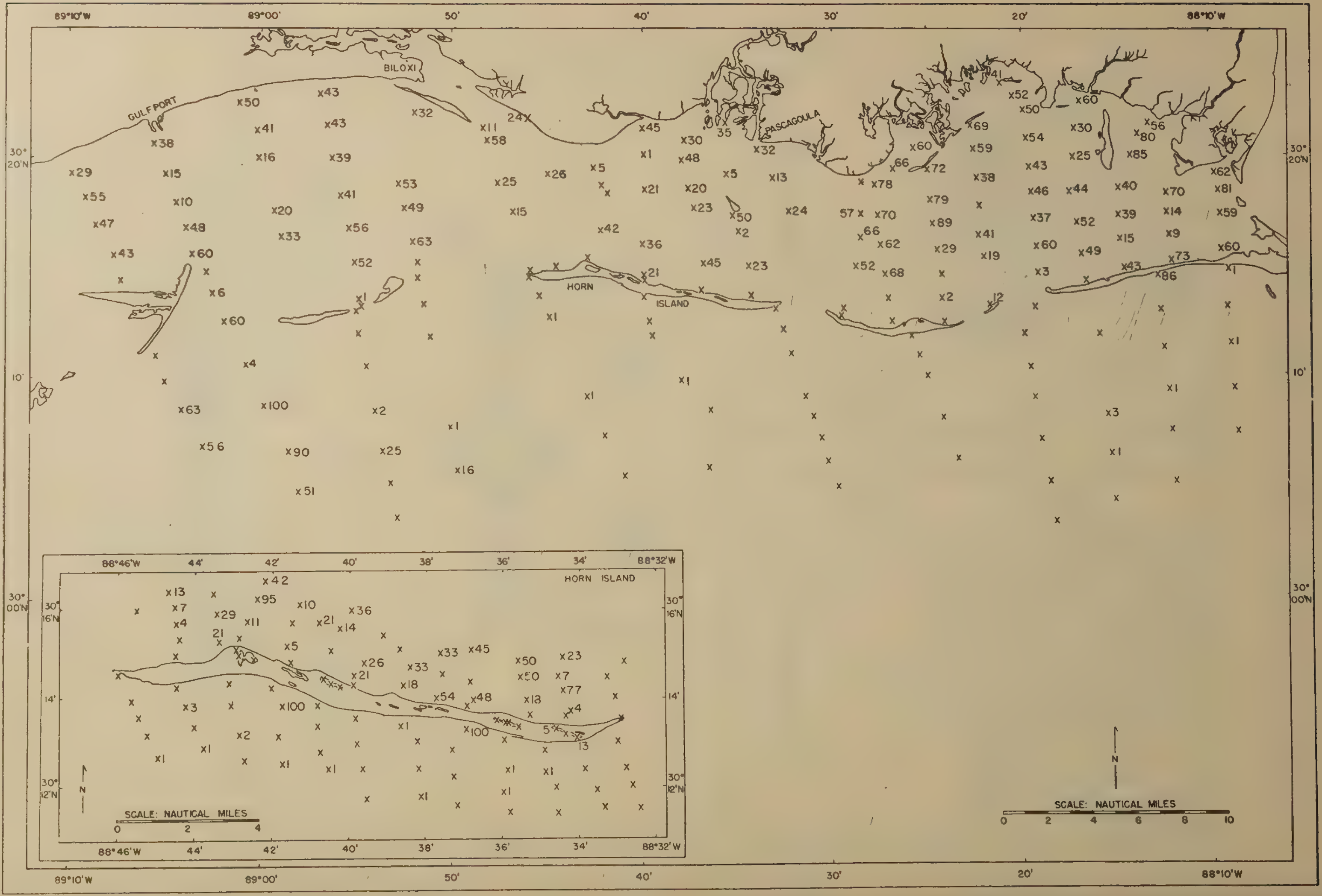

PASCAGOULA RIVER AREA
88°38'
36'
88°34'
30° 24'
22'
30° 20'
23
27
2
3
2
17
1
30
1
PASCA-GOULA
SCALE NAUTICAL MILES
0 1/2 1 2
PT. AUX CHENES AREA
88°30'
28'
88°26'
30° 24'
22'
30° 20'
13
2
20
20
8
2
1
2
15
SCALE. NAUTICAL MILES
0 1/2 1 2
GRAVELINE BAY AREA
88°44'
42'
88°40'
30° 22'
3
70
80
39
1
30
16
22
20
44
19
6
24
2
1
4
19
1
1
4
2
6
17
2
2
16
1
14
4
5
5
49
59
46
13
1
2
4
1
SCALE NAUTICAL MILES
0 1/4 1/2 1

FIG. 10.—Distribution of *Ammobaculites exilis* Cushman and Bronnimann in percentage of total population.


89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
GULFPORT
BILOXI
PASCAGOULA
HORN
ISLAND
x29
x55
x47
x43
x38
x15
x10
x48
x60
x6
x60
x4
x63
x56
x50
x41
x16
x20
x33
x100
x90
x51
x43
x43
x39
x41
x56
x52
x32
x53
x49
x63
x2
x25
x1
x16
x11
x58
24
x25
x15
x26
x5
x42
x1
x45
x1
x21
x36
x21
x30
x48
x20
x23
35
x5
x50
x2
x45
x32
x13
x23
x24
x1
x1
57
x70
x66
x62
x52
x68
x78
x66
x60
x72
x79
x89
x29
x2
x69
x59
x38
x41
x19
12
x52
x50
x54
x43
x46
x37
x60
x3
x60
x30
x25
x44
x52
x49
x40
x39
x15
x43
x56
x80
x85
x70
x14
x9
x73
x86
x62
x81
x59
x60
x1
x3
x1
x1
x1
HORN ISLAND
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
x13
x7
x4
x29
21
x11
x42
x95
x10
x21
x14
x36
x5
x26
x21
x33
x18
x33
x45
x54
x48
x50
x50
x13
x23
x7
x77
x4
5
13
x100
x3
x100
x2
x1
x1
x1
x1
x1
x1
x1
x1
N
SCALE: NAUTICAL MILES
0
2
4
N
SCALE: NAUTICAL MILES
0
2
4
6
8
10

Distribution of Ammobaculites salsus Cushman and Brönnimann in percentage of total population

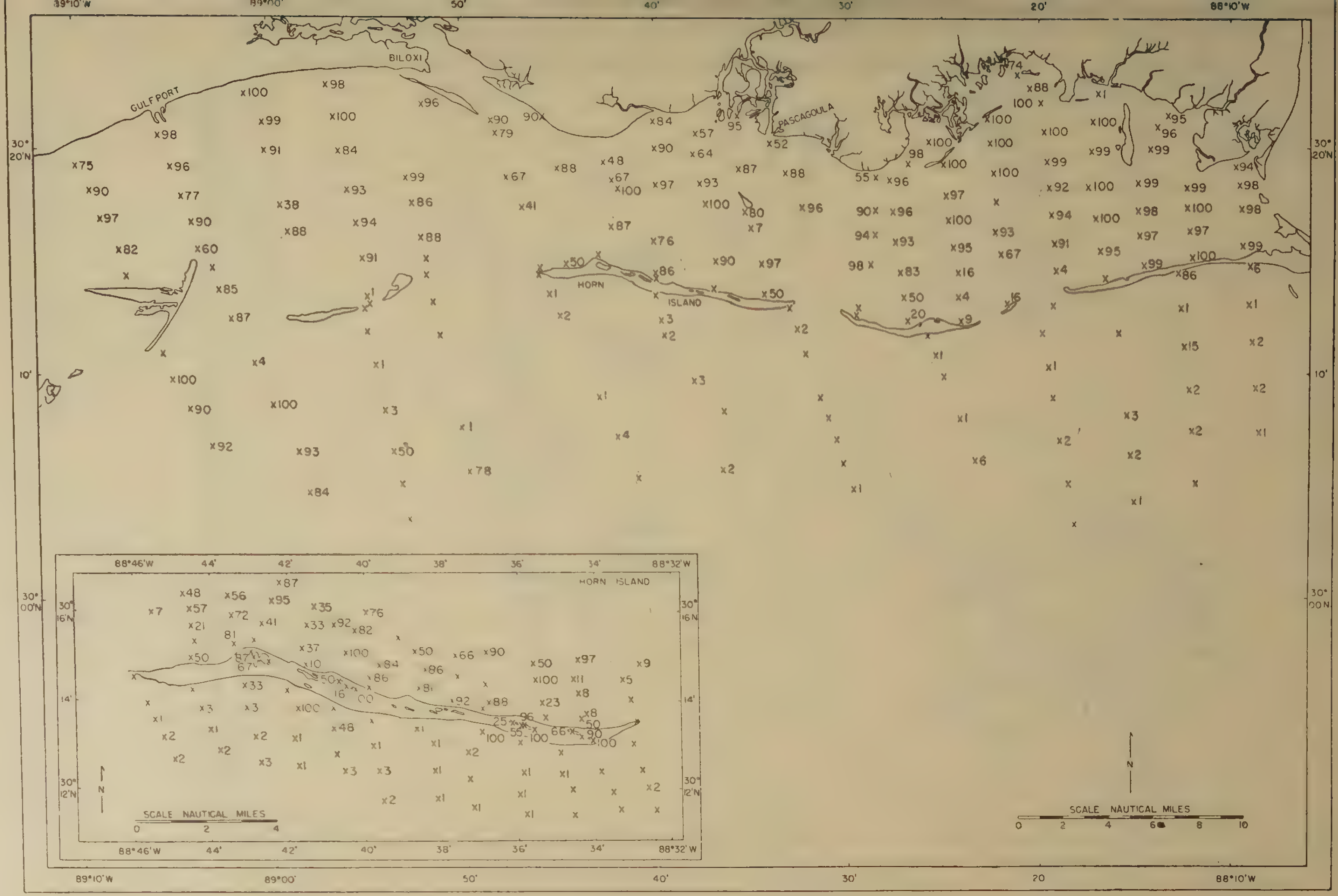
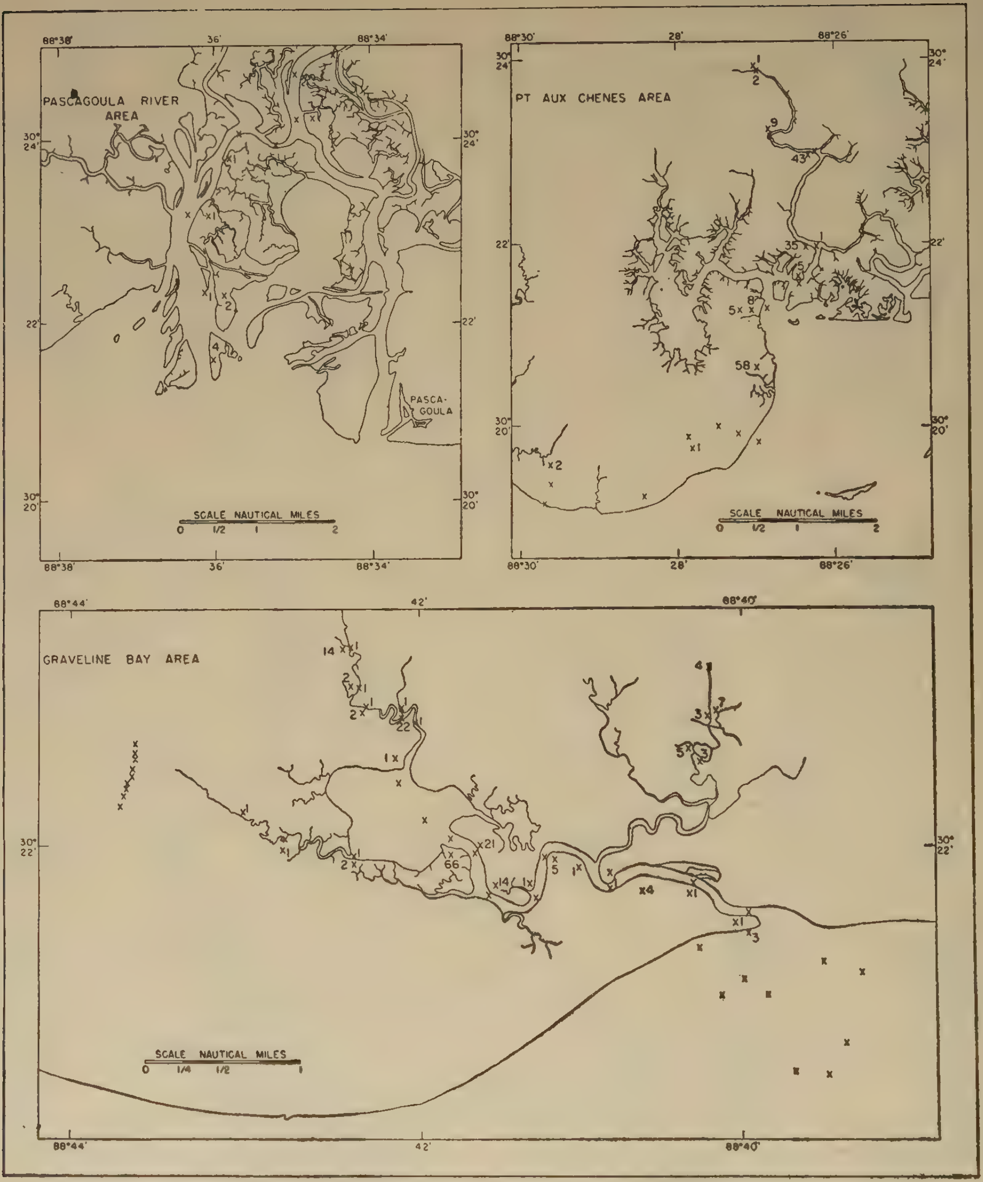

GULFPORT
BILOXI
PASCAGOULA
HORN ISLAND
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
88°46'W
44'
42'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
N
SCALE NAUTICAL MILES
0
2
4
6
8
10

FIG. 12.—Distribution of *Ammobaculites* spp. in percentage of total population.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PASCA-GOULA
SCALE NAUTICAL MILES
0 1/2 1 2
88°38' 36' 88°34'
30° 24'
22'
30° 20'
PT AUX CHENES AREA
SCALE NAUTICAL MILES
0 1/2 1 2
88°30' 28' 88°26'
30° 24'
22'
30° 20'
GRAVELINE BAY AREA
SCALE NAUTICAL MILES
0 1/4 1/2 1
88°44' 42' 88°40'
30° 22'

FIG. 13.—Distribution of *Arenoparrella mexicana* (Kornfeld) in percentage of total population.

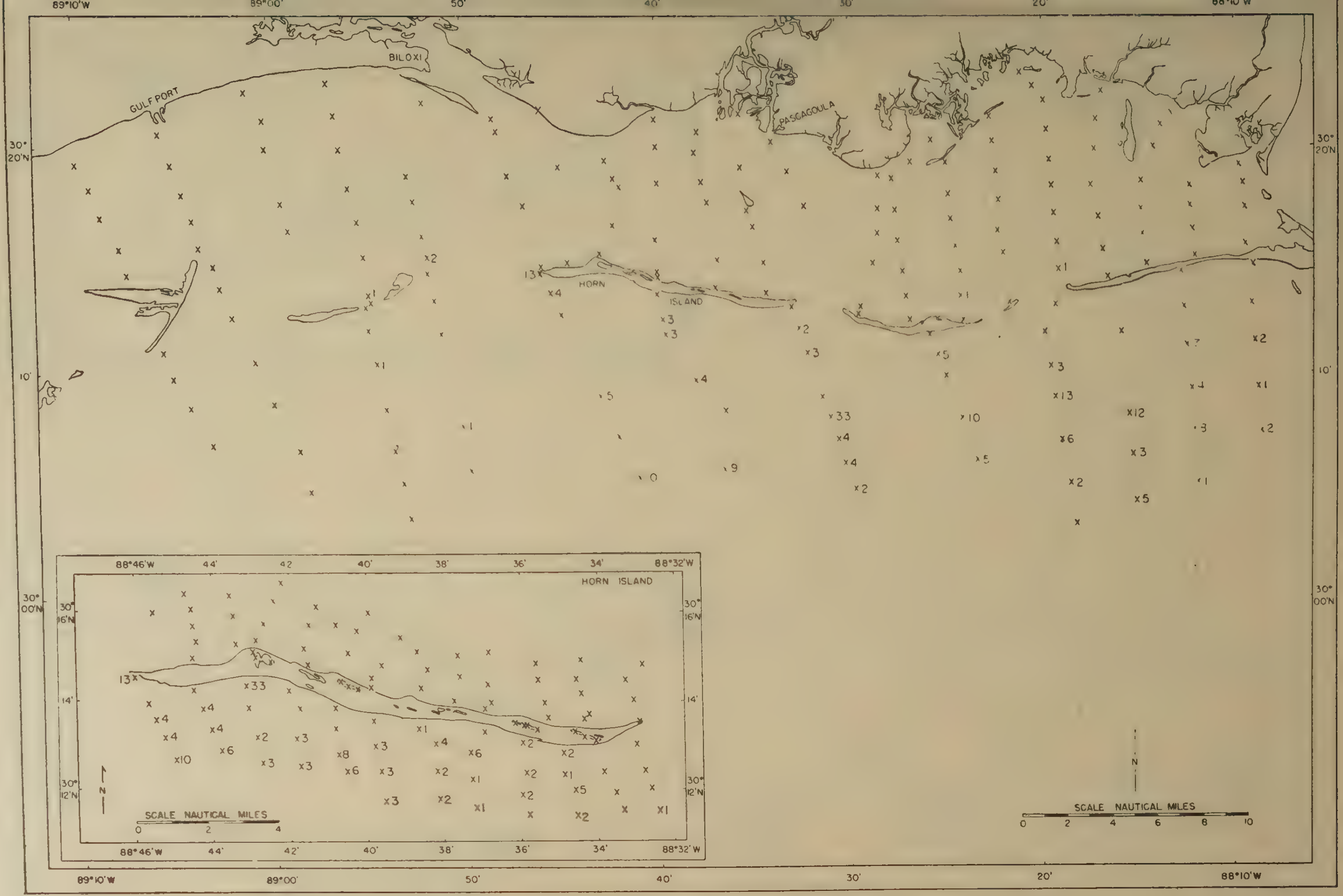

GULF PORT
BILOXI
PASCAGOULA
HORN
ISLAND
HORN ISLAND
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
N
SCALE NAUTICAL MILES
0
2
4
6
8
10

Fig. 14.—Distribution of *Bigenerina irregularis* Phleger and Parker in percentage of total population.

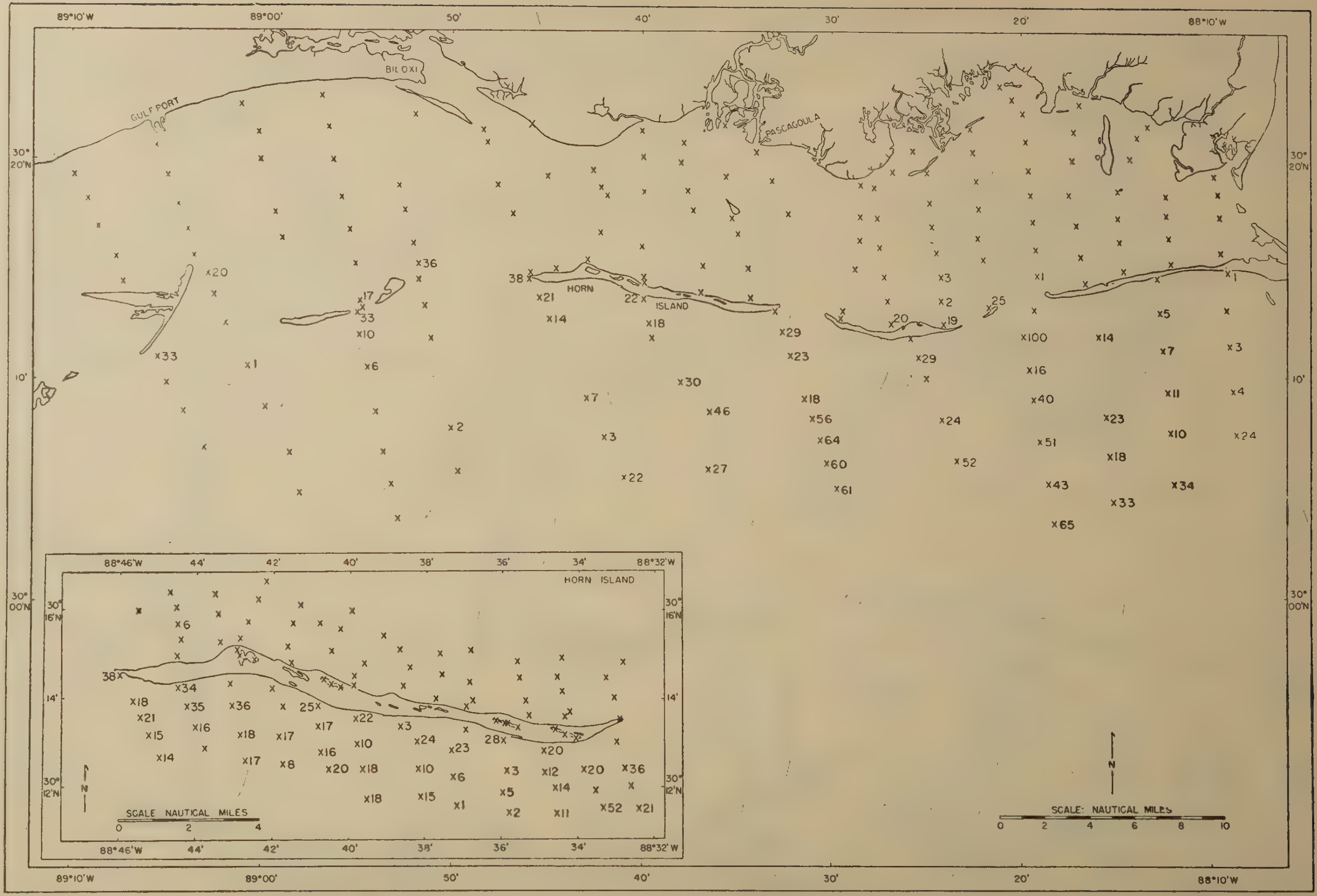

GULF PORT
BILOXI
PASCAGOULA
HORN ISLAND
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
SCALE: NAUTICAL MILES
0
2
4
6
8
10
N
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
SCALE NAUTICAL MILES
0
2
4

FIG. 15.—Distribution of *Cibicidina strattoni* (Applin) in percentage of total population.

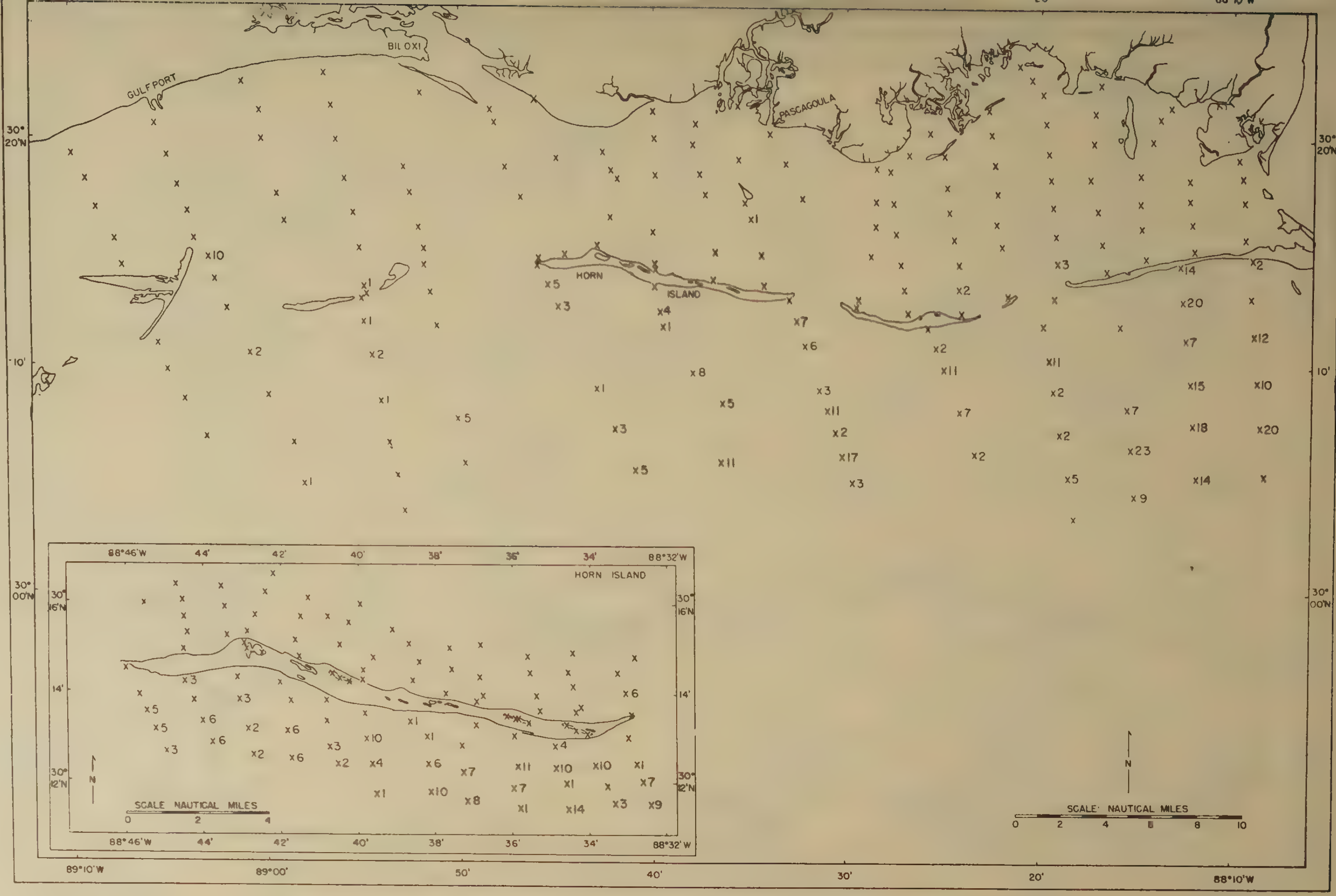
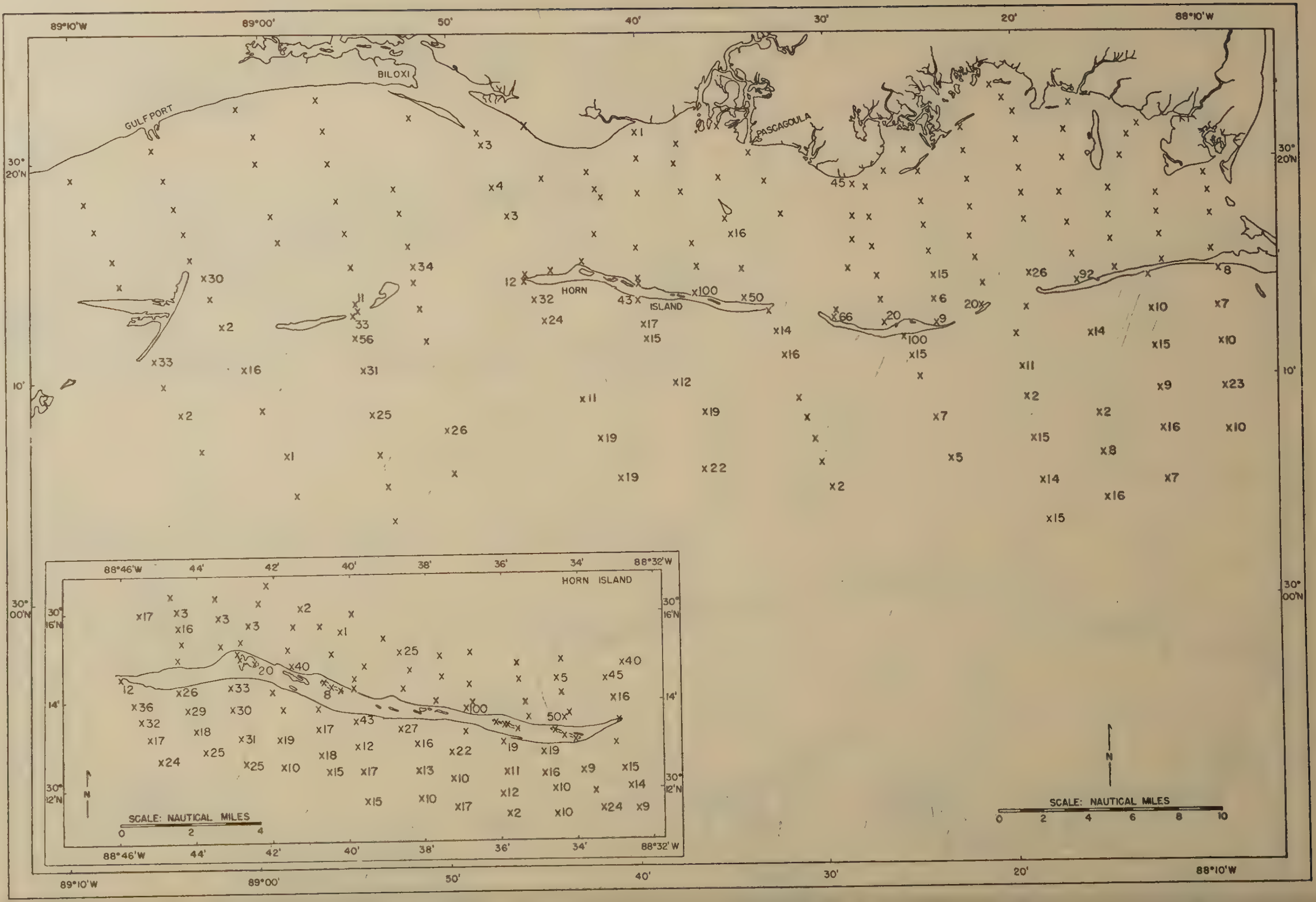

GULFPORT
BILOXI
PASCAGOULA
HORN ISLAND
30° 20'N
10'
30° 00'N
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
SCALE NAUTICAL MILES
0 2 4 6 8 10
N
HORN ISLAND
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
SCALE NAUTICAL MILES
0 2 4

FIG. 16.—Distribution of *Discorbis* cf. *columbiensis* Cushman in percentage of total population.


89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
GULFPORT
BILOXI
PASCAGOULA
HORN
ISLAND
N
SCALE: NAUTICAL MILES
0
2
4
6
8
10
HORN ISLAND
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
SCALE: NAUTICAL MILES
0
2
4

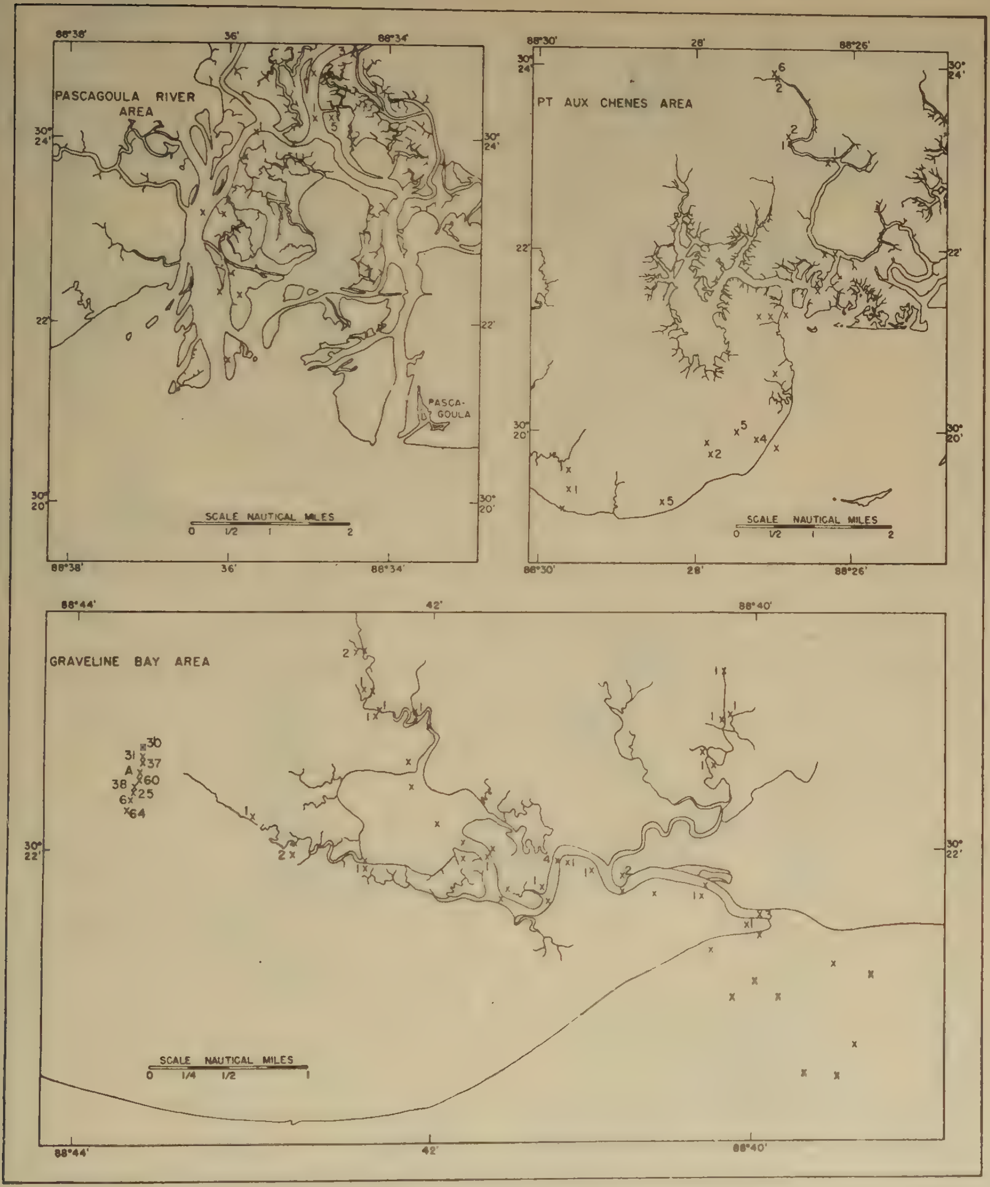

PASCAGOULA RIVER AREA
88°38'
36'
88°34'
30° 24'
22'
30° 20'
PASCAGOULA
SCALE NAUTICAL MILES
0 1/2 1 2
PT AUX CHENES AREA
88°30'
28'
88°26'
30° 24'
22'
30° 20'
SCALE NAUTICAL MILES
0 1/2 1 2
GRAVELINE BAY AREA
88°44'
42'
88°40'
30° 22'
30
31
37
A
38
60
25
6
64
SCALE NAUTICAL MILES
0 1/4 1/2 1

FIG. 18.—Distribution of *Leptodermella variabilis* Parker in percentage of total population.

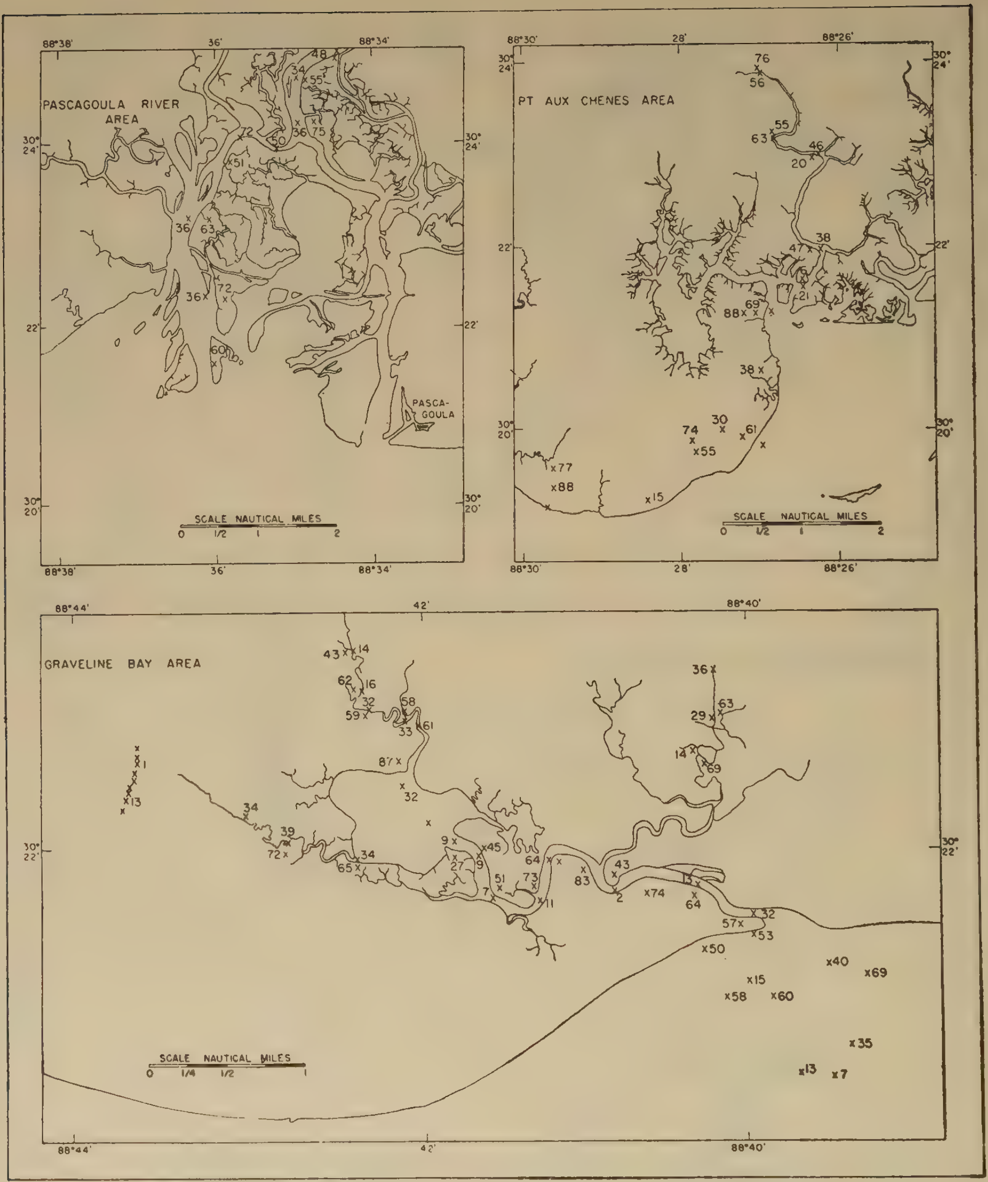

PASCAGOULA RIVER AREA
88°38'
36'
88°34'
30° 24'
22'
30° 20'
PASCAGOULA
SCALE NAUTICAL MILES
0 1/2 1 2
48
34
55
36
75
72
50
51
36
63
36
72
60
PT AUX CHENES AREA
88°30'
28'
88°26'
30° 24'
22'
30° 20'
76
56
55
63
46
20
38
47
69
88
21
38
30
74
61
55
77
88
15
SCALE NAUTICAL MILES
0 1/2 1 2
GRAVELINE BAY AREA
88°44'
42'
88°40'
30° 22'
43
14
62
16
32
59
58
33
61
87
32
1
13
34
39
72
34
65
9
45
27
9
51
7
73
11
64
83
43
2
74
64
13
32
57
53
50
36
63
29
14
69
40
69
15
58
60
35
13
7
SCALE NAUTICAL MILES
0 1/4 1/2 1

FIG. 19.—Distribution of *Miliammina fusca* (H. B. Brady) in marsh and estuary samples, in percentage of total population.

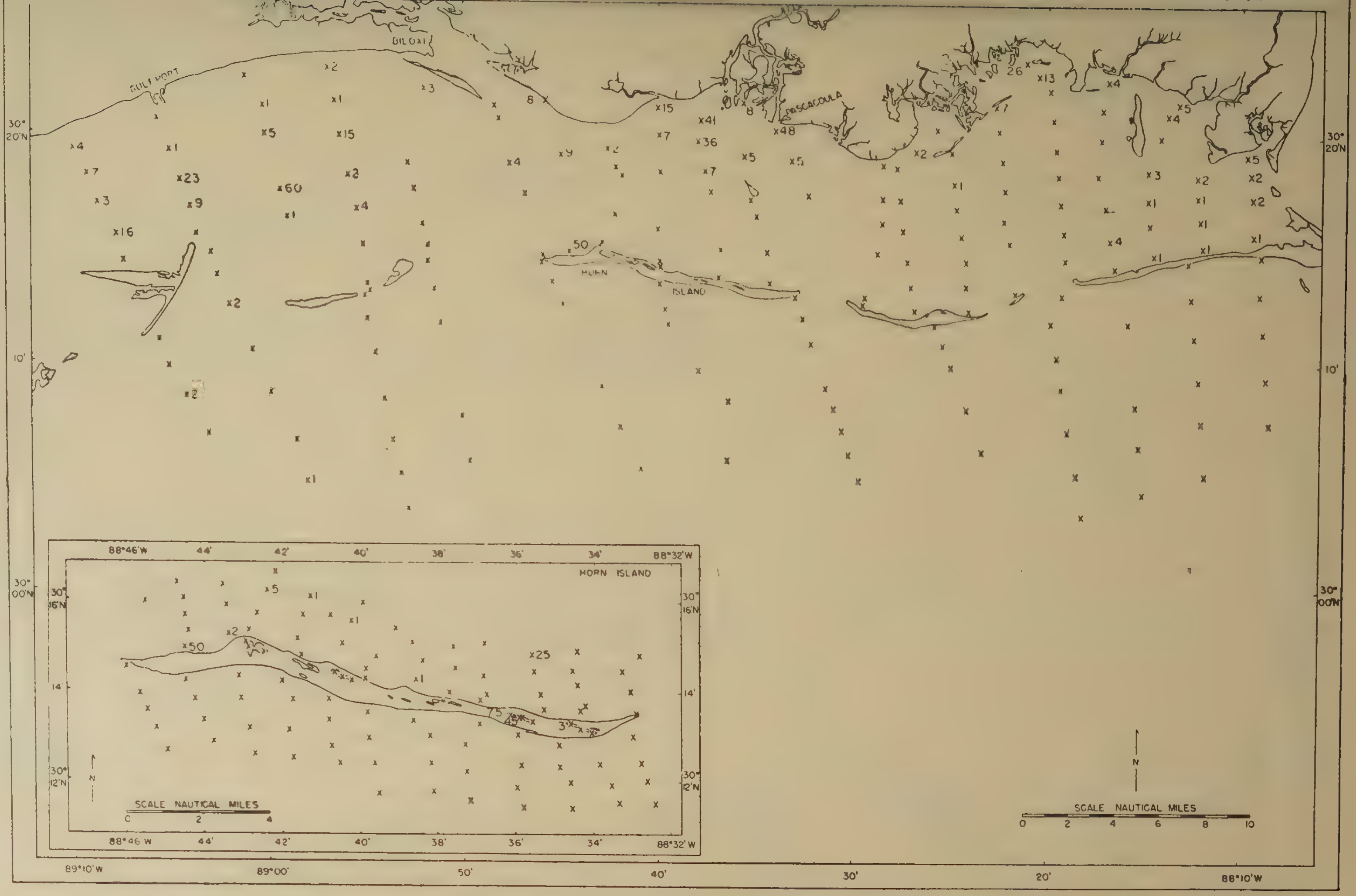
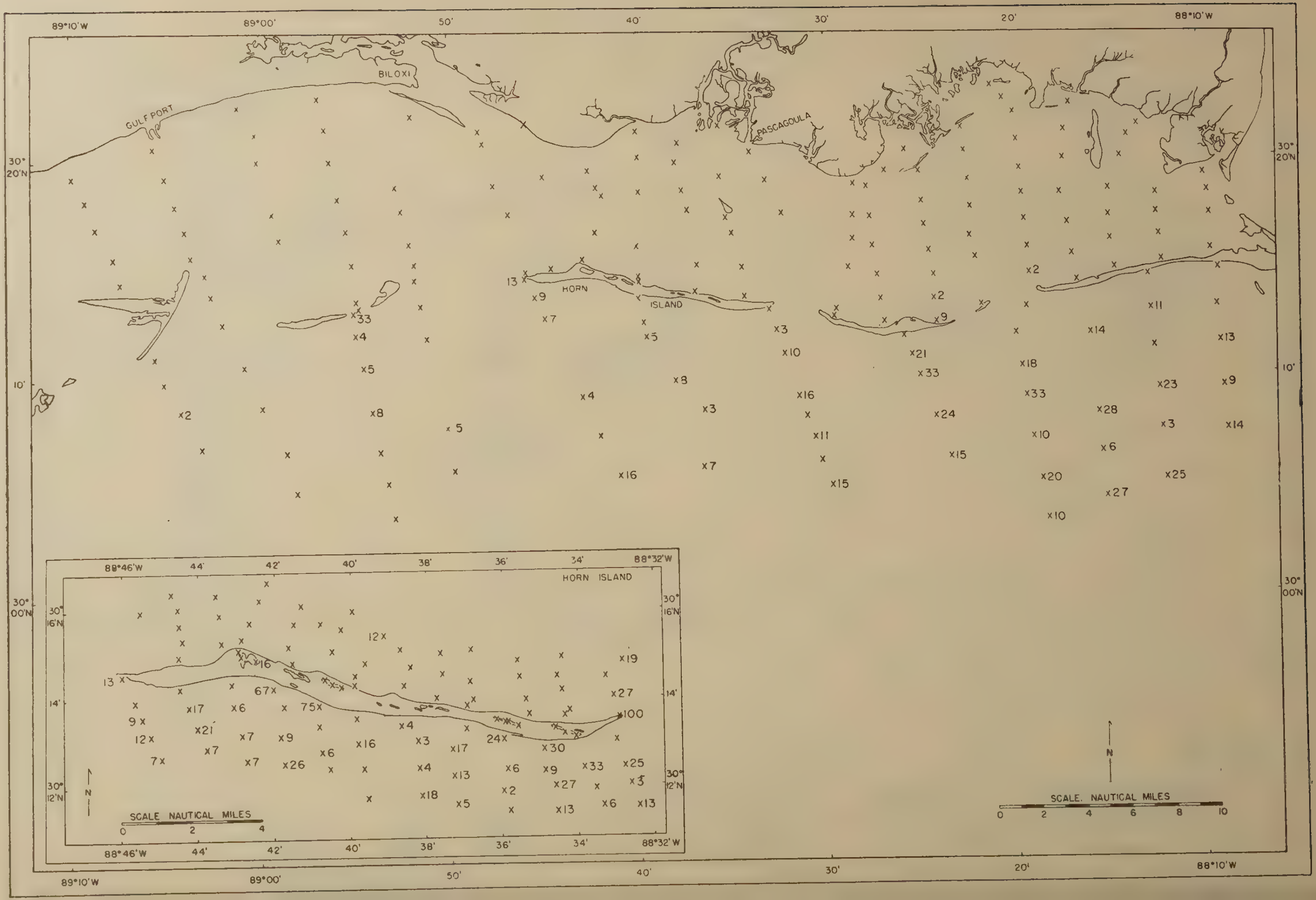

GULFPORT
BILOXI
PASCAGOULA
HORN ISLAND
HORN ISLAND
30° 20'N
10'
30° 00'N
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
N
SCALE NAUTICAL MILES
0
2
4
6
8
10
SCALE NAUTICAL MILES
0
2
4

FIG. 20.—Distribution of *Miliammina fusca* (H. B. Brady) in Mississippi Sound, in percentage of total population.


89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
GULF PORT
BILOXI
PASCAGOULA
HORN
ISLAND
SCALE NAUTICAL MILES
0
2
4
6
8
10
N
HORN ISLAND
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
SCALE NAUTICAL MILES
0
2
4
100
75
67
24
13

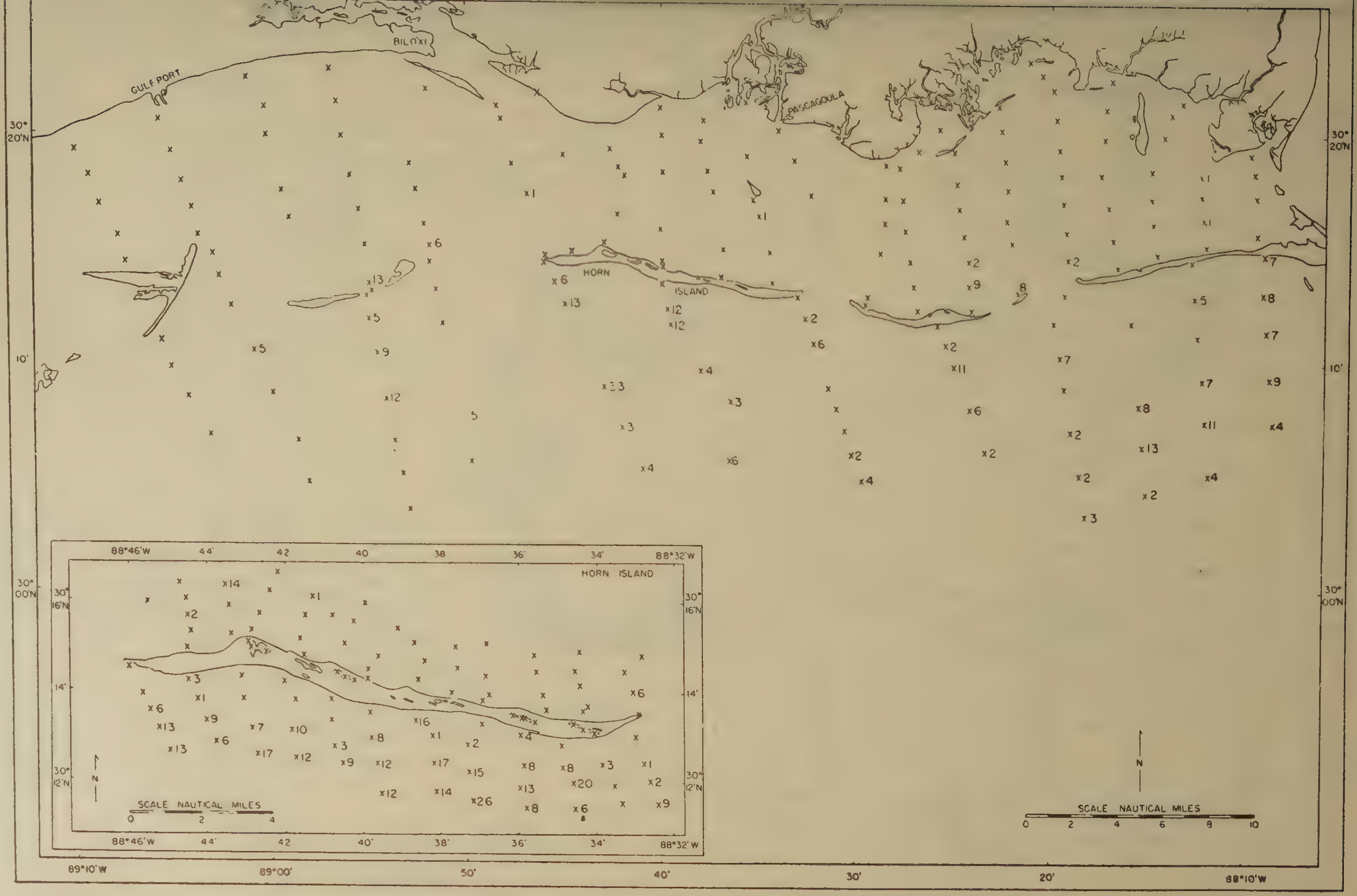
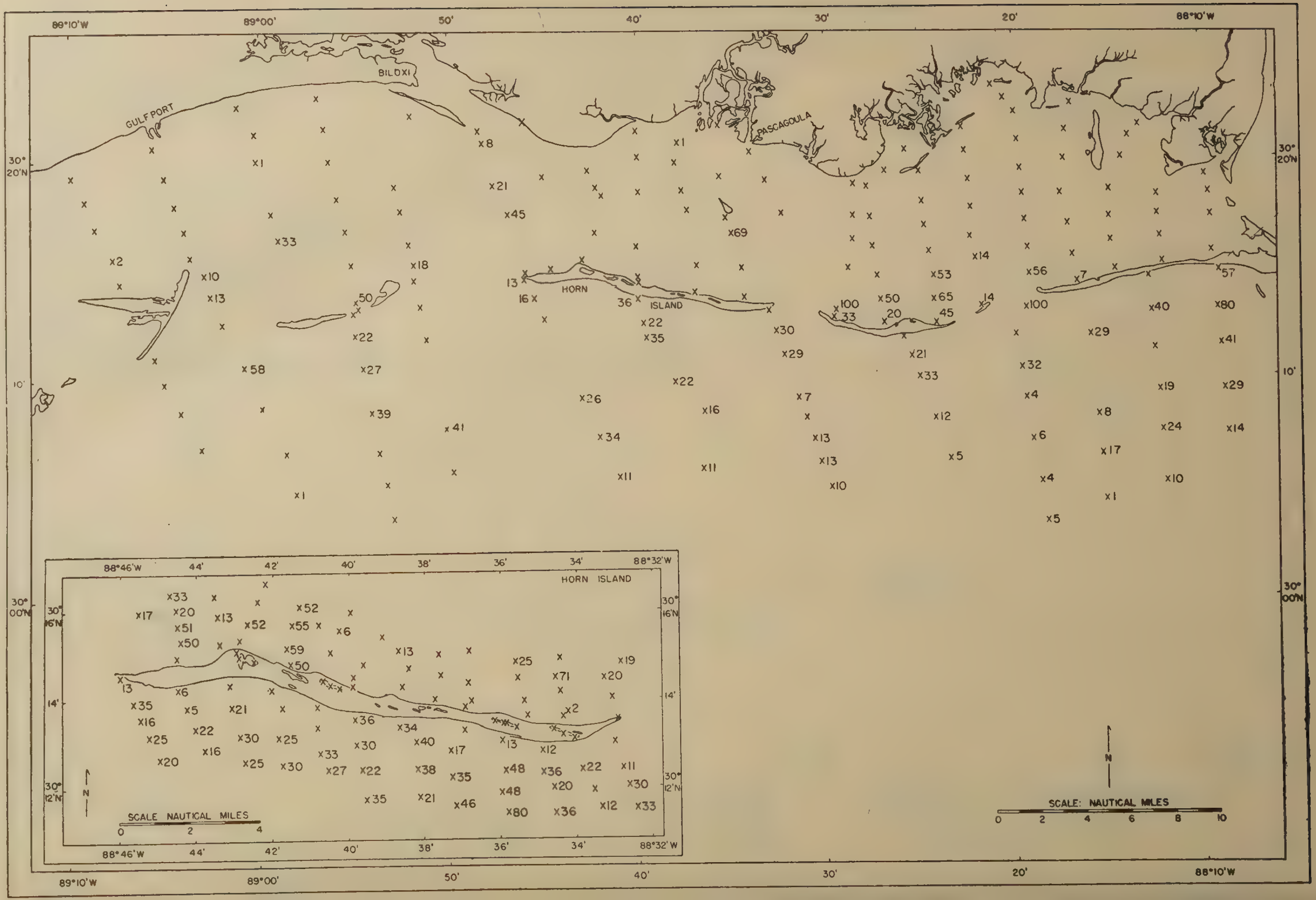

GULF PORT
BILOXI
PASCAGOULA
HORN ISLAND
30° 20'N
10'
30° 00'N
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
N
SCALE NAUTICAL MILES
0 2 4 6 8 10
HORN ISLAND
88°46'W
44'
42
40
38
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
SCALE NAUTICAL MILES
0 2 4

FIG. 22.—Distribution of *Nonionella atlantica* Cushman in percentage of total population.


GULF PORT
BILOXI
PASCAGOULA
HORN ISLAND
89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
SCALE: NAUTICAL MILES
0 2 4 6 8 10
N
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
SCALE NAUTICAL MILES
0 2 4

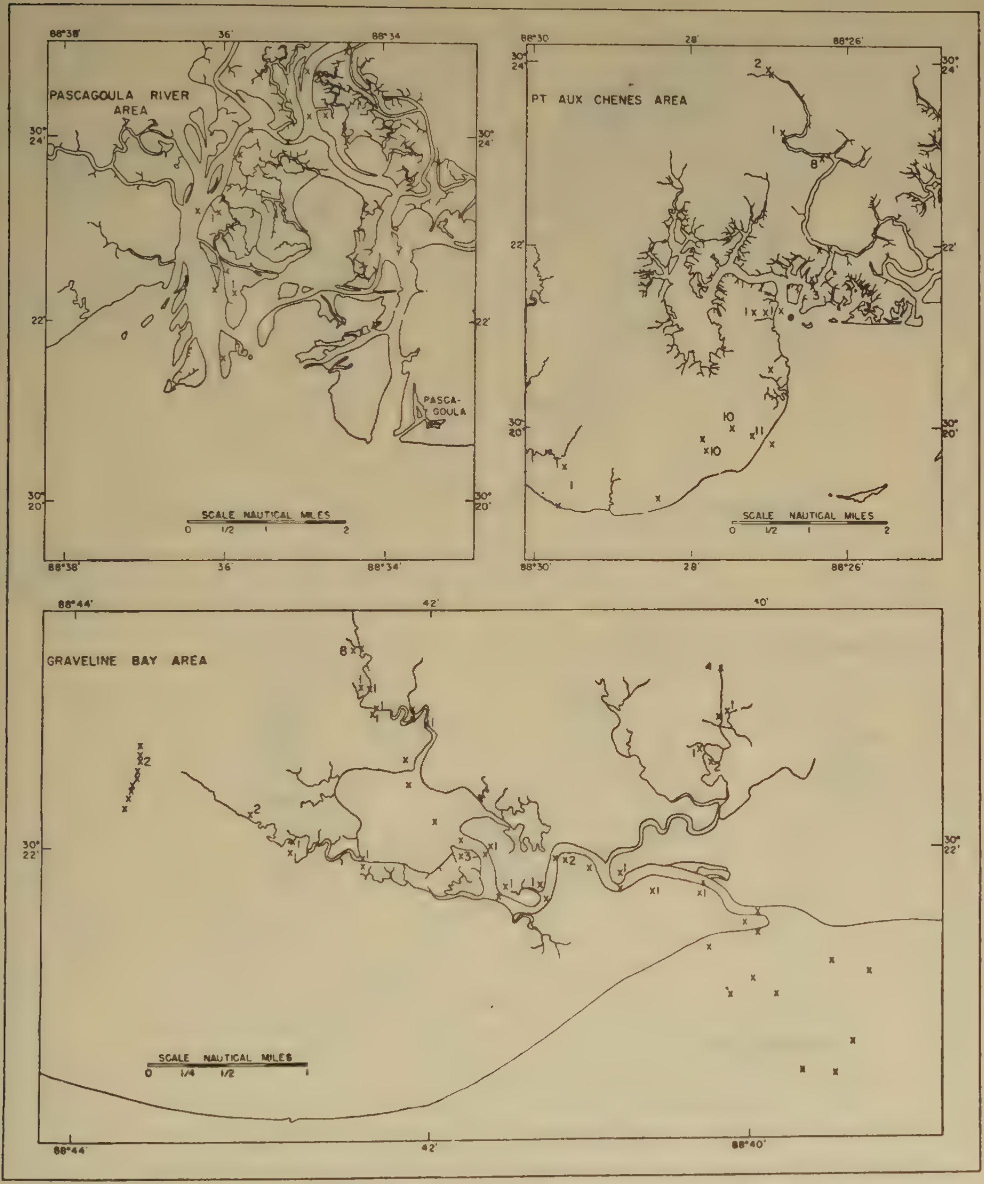

PASCAGOULA RIVER AREA
PASCA-GOULA
PT AUX CHENES AREA
GRAVELINE BAY AREA
SCALE NAUTICAL MILES
88°38'
36'
88°34'
88°30'
28'
88°26'
88°44'
42'
40'
88°40'
30° 24'
22'
30° 20'
30° 22'

FIG. 24.—Distribution of *Trochammina macrescens* H. B. Brady in percentage of total population.

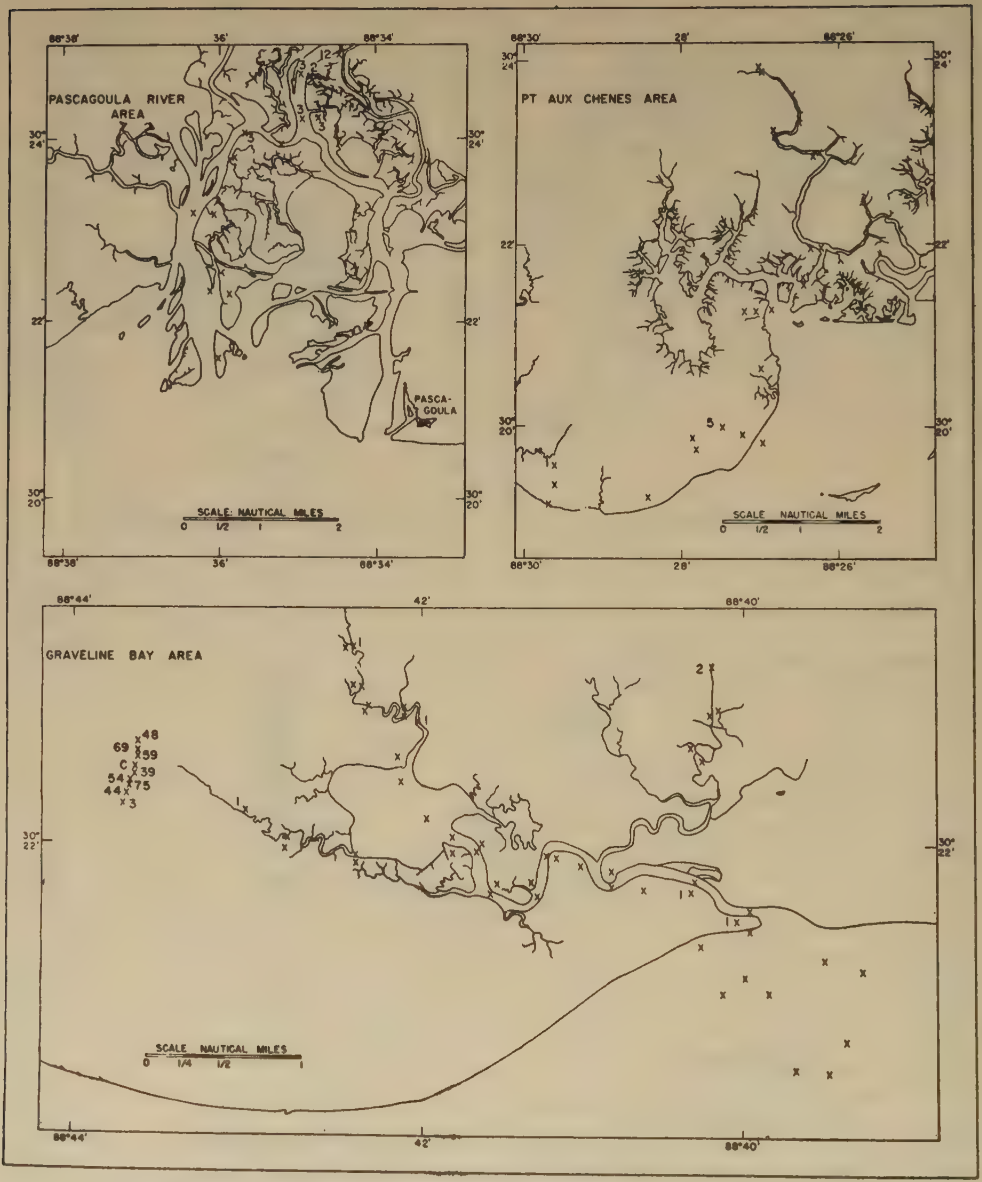

PASCAGOULA RIVER AREA
88°38'
36'
88°34'
30° 24'
22'
30° 20'
12
2
3
3
3
PASCA-GOULA
SCALE: NAUTICAL MILES
0 1/2 1 2
PT AUX CHENES AREA
88°30'
28'
88°26'
30° 24'
22'
30° 20'
5
SCALE NAUTICAL MILES
0 1/2 1 2
GRAVELINE BAY AREA
88°44'
42'
88°40'
30° 22'
48
69
59
C
39
54
75
44
3
1
1
1
2
1
1
SCALE NAUTICAL MILES
0 1/4 1/2 1

FIG. 25.—Distribution of *Urnulina* spp. in percentage of total population.

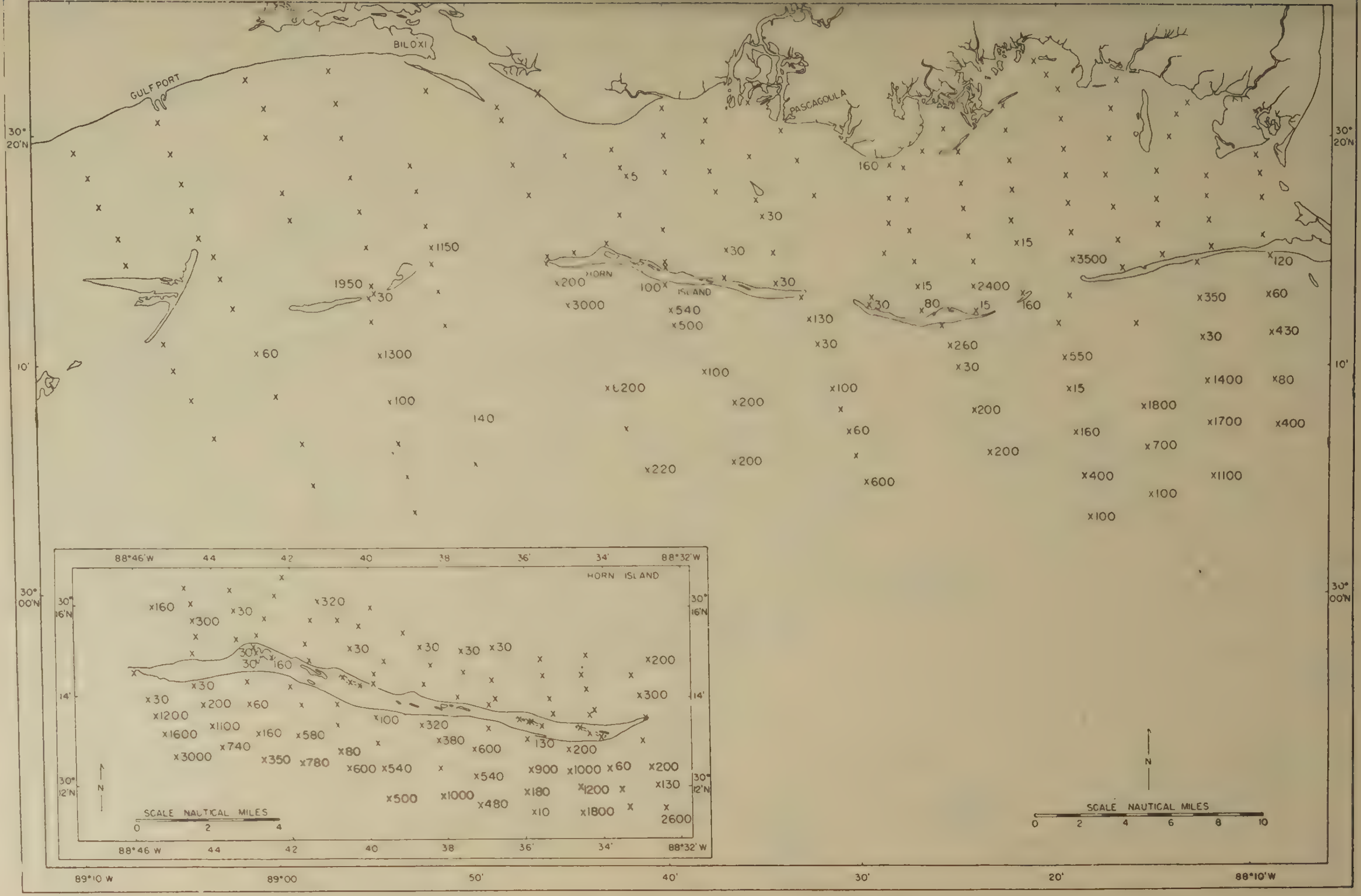
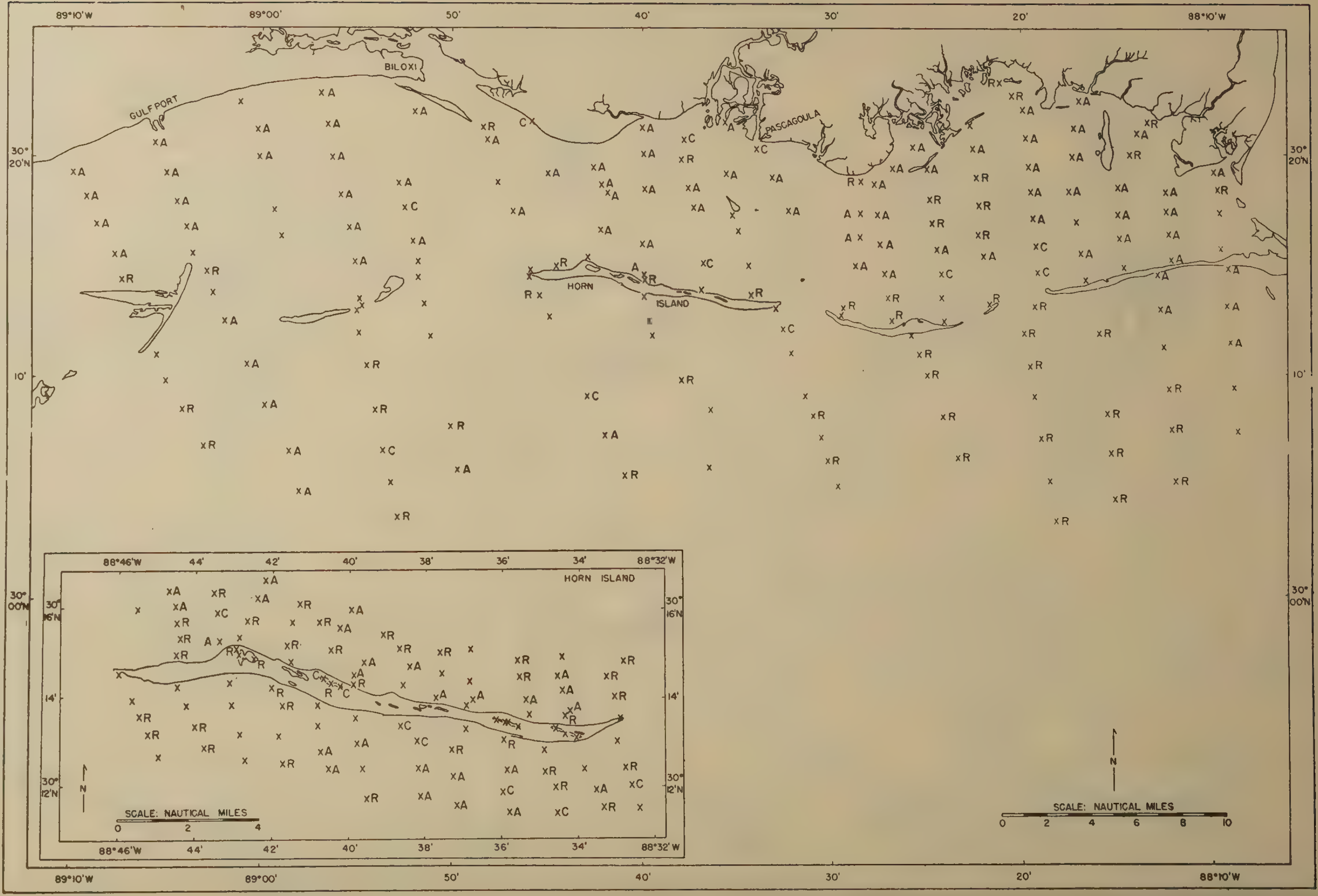

GULFPORT
BILOXI
PASCAGOULA
HORN ISLAND
30° 20'N
10'
30° 00'N
89°10 W
89°00
50'
40'
30'
20'
88°10'W
SCALE NAUTICAL MILES
0 2 4 6 8 10
N
x1150
1950
x30
x60
x1300
x100
140
x200
x3000
100
x540
x500
x30
x5
x L200
x100
x200
x220
x200
x130
x30
x100
x60
x600
160
x15
x2400
x15
x30
80
15
160
x260
x30
x200
x200
x3500
x550
x15
x160
x400
x100
x1800
x700
x100
x350
x30
x1400
x1700
x1100
120
x60
x430
x80
x400
88°46'W
44
42
40
38
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
x160
x300
x30
x320
x30
x30
x30
x30
30
30
160
x200
x300
x30
x30
x200
x60
x1200
x1100
x160
x580
x100
x320
x1600
x740
x380
x600
x130
x200
x3000
x350
x780
x80
x600
x540
x540
x900
x1000
x60
x200
x500
x1000
x480
x180
1200
x130
x10
x1800
2600
SCALE NAUTICAL MILES
0 2 4

FIG. 26.—Distribution of Ostracoda total population.


89°10'W
89°00'
50'
40'
30'
20'
88°10'W
30° 20'N
10'
30° 00'N
GULFPORT
BILOXI
PASCAGOULA
HORN ISLAND
HORN ISLAND
88°46'W
44'
42'
40'
38'
36'
34'
88°32'W
30° 16'N
14'
30° 12'N
N
SCALE: NAUTICAL MILES
0
2
4
N
SCALE: NAUTICAL MILES
0
2
4
6
8
10

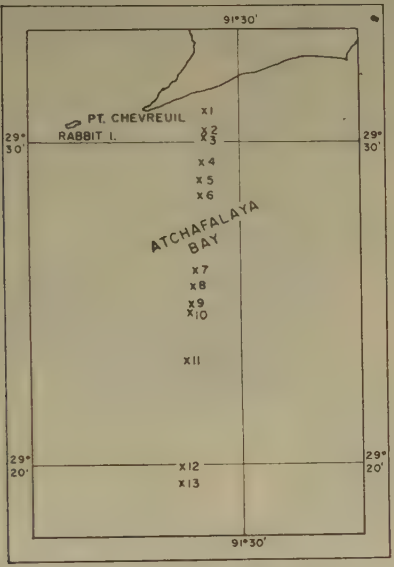


FIG. 28.—Locations of stations off Atchafalaya Bay.

Ammoastuta inepta (Cushman and McCulloch)

Plate 1, Figures 1–3

Ammobaculites ineptus Cushman and McCulloch, 1939, Allan Hancock Pacific Exped., vol. 6, no. 1, p. 89, pl. 7, fig. 6.

Ammoastuta salsa Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 17, pl. 3, figs. 14–16.

In the Mississippi Sound area this species is characteristic of the marsh facies occurring at most of the stations in frequencies as high as 25% or more. It also is present in the estuaries but in much lower per cents. It is not present at the inner marsh stations west of Graveline Bay, and may not be characteristic of innermost marsh areas.

Ammobaculites cf. dilatatus Cushman and Bronnimann

Plate 1, Figure 4

Ammobaculites dilatatus Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 39, pl. 7, figs. 10, 11.

This species occurs at several stations in Mississippi Sound and adjacent open gulf areas at frequencies generally 1% or less and seldom greater than 5%. It is possible that more than one species are included under this designation in that area.

Ammobaculites exiguus Cushman and Bronnimann

Plate 1, Figure 5

Ammobaculites exiguus Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 38, pl. 7, figs. 7, 8.

This species is confined to the Mississippi Sound facies where it occurs at approximately half the stations at frequencies less than 5%. It occurs in the extreme western part of the open-gulf area but not elsewhere in this facies. It is present at two stations on

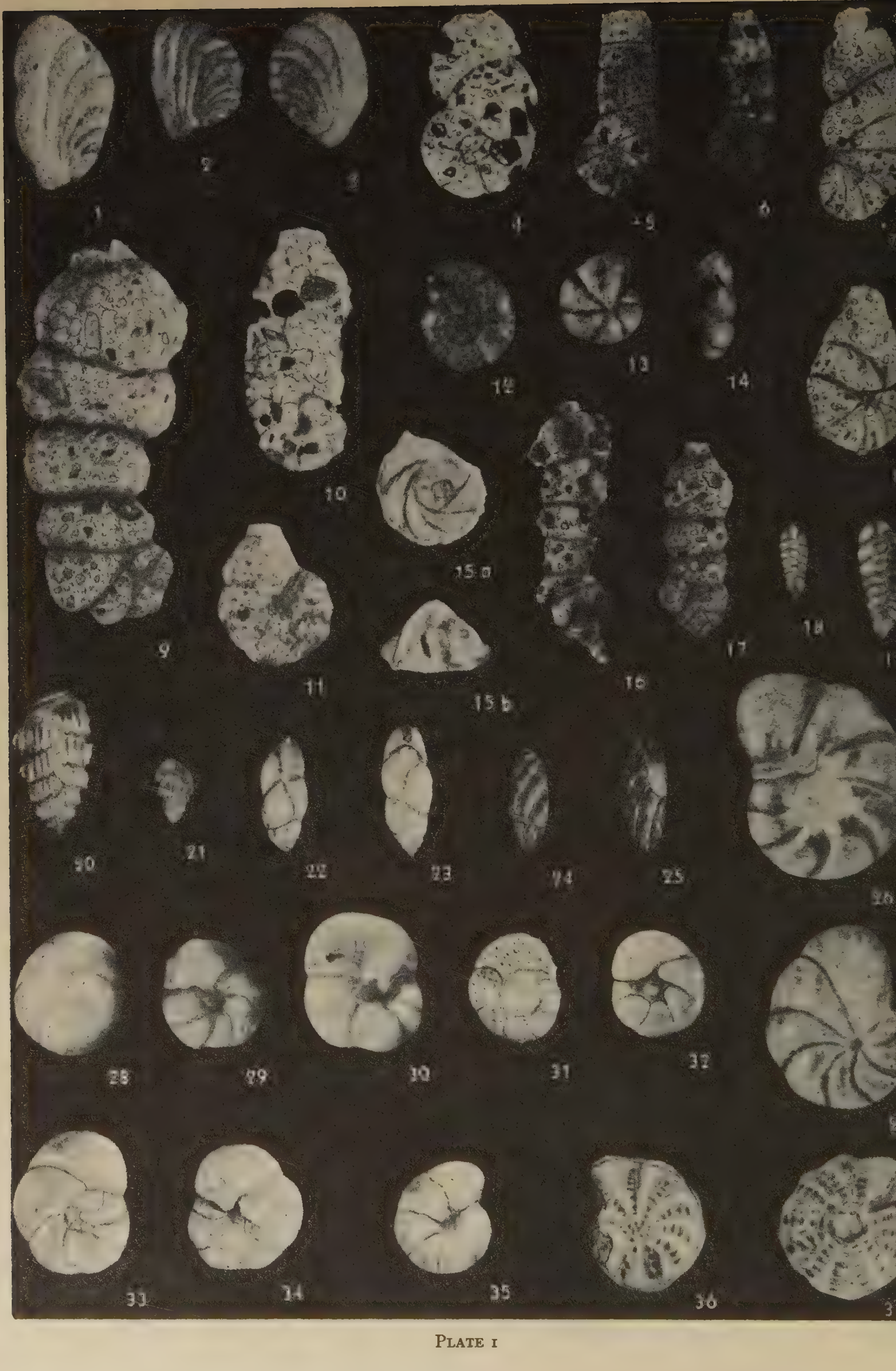

1
2
3
4
5
6
9
10
11
12
13
14
15 a
15 b
16
17
18
20
21
22
23
24
25
26
28
29
30
31
32
33
34
35
36

Plate 1

the eastern end of Horn Island and at two on Isle aux Herbes. It also occurs in very low frequencies at a few estuary stations.

Ammobaculites exilis Cushman and Bronnimann

Plate 1, Figure 6

Ammobaculites exilis Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 39, pl. 7, fig. 9.

This species is essentially confined to the marsh and estuary facies in the Mississippi Sound area and occurs at most of those stations. It is much more abundant in the estuaries than in the marsh, with frequencies up to 50%. It occurs at all stations in Graveline Bay in frequencies 20–44%. It is in very low frequencies off the mouth of Graveline Bayou but is present at essentially no other sound stations.

Ammobaculites salsus Cushman and Bronnimann

Plate 1, Figures 7, 8

Ammobaculites salsus Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 16, pl. 3, figs. 7–9.

In the Mississippi Sound area this is the dominant member of the sound facies, occurring at essentially all sound stations with frequencies generally greater than 20% and commonly more than 50%. It also occurs in significant abundances at the majority of marsh stations at 1–5%. It is present at numerous open-gulf stations, usually at 1% or less of the fauna, except in the western part of the open-gulf area where frequencies are similar to those in the sound. More than one species or variety may be included under this name in this area. Most of the specimens identified as *Ammobaculites* sp. should be included here.

EXPLANATION OF PLATE 1

FIGS.

1–3. *Ammoastuta inepta* (Cushman and McCulloch). 1, ×75; 2, 3, ×48. 1, Miss. Delta Sta. 28; 2, 3, Miss. Sd. Sta. 969.

4. *Ammobaculites* cf. *dilatatus* Cushman and Bronnimann. ×48. Miss. Sd. Sta. 1265.

5. *Ammobaculites exiguus* Cushman and Bronnimann. ×48. Miss. Sd. Sta. 975.

6. *Ammobaculites exilis* Cushman and Bronnimann. ×48. Miss. Sd. Sta. 995.

7, 8. *Ammobaculites salsus* Cushman and Bronnimann. 7, ×56; 8, ×75. Miss. Delta Sta. 23.

9. *Ammobaculites* sp. B. ×52. Miss. Sd. Sta. 1051.

10. *Ammoscalaria pseudospiralis* (Williamson). ×56. Miss. Delta Sta. 37.

11. *Ammoscalaria fluvialis* Parker. ×75. Miss. Sd. Sta. 969.

12–14. *Arenoparrella mexicana* (Kornfeld). ×48. Miss. Sd. Sta. 1007.

15a, b. *Asterigerina carinata* d'Orbigny. ×75. Miss. Sd. Sta. 1229.

16, 17. *Bigenerina irregularis* Phleger and Parker. ×48. 16, Miss. Sd. Sta. 1264; 17, Miss. Sd. Sta. 1228.

18, 19. *Bolivina lowmani* Phleger and Parker. ×75. Miss. Sd. Sta. 1228.

20. *Bolivina pulchella* (d'Orbigny) var. *primitiva* Cushman. ×75. Miss. Sd. Sta. 1240.

21. *Bulimina* cf. *striata* d'Orbigny. ×50. Miss. Sd. Sta. 1228.

22, 23. *Buliminella* cf. *bassendorfensis* Cushman and Parker. ×75. 22, Miss. Sd. Sta. 1228; 23, Miss. Delta Sta. 71.

24, 25. *Buliminella elegantissima* (d'Orbigny). ×75. Miss. Delta Sta. 35.

26, 27. *Cibicidina strattoni* (Applin). ×75. Miss. Sd. Sta. 1228.

28, 29, 31, 32. *Discorbis* cf. *columbiensis* Cushman. 28, 29, 32, ×75; 31, ×48. 28, 29, Miss. Sd. Sta. 1228; 31, 32, Miss. Sd. Sta. 1240.

30, 33, 34. *Discorbis floridana* Cushman. 30, ×75; 33, 34, ×56. 30, 34, Miss. Sd. Sta. 1240; 33, Miss. Sd. Sta. 1228.

35. *Elphidium delicatulum* Bermudez. ×75. Miss. Delta Sta. 252.

36. *Elphidium advenum* (Cushman). ×56. Miss. Delta Sta. 75.

37. *Elphidium discoidale* (d'Orbigny). ×48. Miss. Sd. Sta. 1228.

Ammobaculites sp. B

Plate 1, Figure 9

Ammobaculites sp. B, 1953, Parker, Phleger, and Peirson, Cushman Found. Foram. Res., Spec. Publ. No. 2, p. 5, pl. 1, fig. 30.

This form is present in very low frequencies at a few stations in Mississippi Sound. It was not separated in the frequency tabulation.

Ammoscalaria fluvialis Parker

Plate 1, Figure 11

Ammoscalaria fluvialis Parker, 1952, Bull. Mus. Comp. Zool., vol. 106, p. 444, pl. 1, figs. 24, 25.

This species is abundant in the estuaries and marshes in the Mississippi Sound area with generally higher frequencies in the streams. The average frequencies are approximately 10–25%, others are higher.

Ammoscalaria pseudospiralis (Williamson)

Plate 1, Figure 10

Proteonina pseudospiralis Williamson, 1858, Rec. Foram. Great Britain, p. 2, pl. 1, figs. 2, 3.

This species occurs in the Mississippi Sound material but was not differentiated, and is included here for completeness. Off the coast of Texas it occurs in the open gulf and lower bays.

Arenoparrella mexicana (Kornfeld)

Plate 1, Figures 12–14

Trochammina inflata (Montagu) var. *mexicana* Kornfeld, 1931, Contr. Dept. Geol. Stanford Univ., vol. 1, p. 86, pl. 13, figs. 5a–c.

This is a marsh species in the Mississippi Sound area which appears to occur in the streams only as a contamination from the marsh deposits. Local frequencies may be 4% or more. It is not present at the inner marsh stations west of Graveline Bay.

Asterigerina carinata d'Orbigny

Plate 1, Figures 15a, b

Asterigerina carinata d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 118, pl. 5, fig. 25, pl. 6, figs. 1, 2.

Occurs only outside the islands in the Mississippi Sound area except at one station behind Horn Island, and is mostly from Horn Island eastward. Frequencies are generally 1–3%.

Bigenerina irregularis Phleger and Parker

Plate 1, Figures 16, 17

Bigenerina irregularis Phleger and Parker, 1951, Geol. Soc. Amer., Mem. 46, pt. 2, p. 4, pl. 1, figs. 16–21.

In the Mississippi Sound area this species is confined to the open-gulf fauna with frequencies which average 5–10%. It also is present inside the pass, east of Petit Bois Island, and at three stations near Ship Island.

Bolivina lowmani Phleger and Parker

Plate 1, Figures 18, 19

Bolivina lowmani Phleger and Parker, 1951, Geol. Soc. Amer., Mem. 46, pt. 2, p. 13, pl. 6, figs. 12a, b, 13.

This species is present at numerous open-gulf stations in the Mississippi Sound area at low frequencies, usually 1–2%, and also at many of the stations in the sound where contamination with the open-gulf fauna occurs.

Bolivina pulchella (d'Orbigny) var. primitiva Cushman

Plate 1, Figure 20

Bolivina pulchella (d'Orbigny) var. *primitiva* Cushman, 1930, Bull. 4, Fla. State Geol. Surv., p. 47, pl. 8, figs. 12a, b.

Present at only a few open-gulf stations in the Mississippi Sound area in frequencies less than 1%.

Bolivina striatula Cushman

Bolivina striatula Cushman, 1922, Publ. 311, Carnegie Inst. Washington, p. 27, pl. 3, fig. 10.

This species is present at only a few open-gulf stations in the Mississippi Sound area at frequencies less than 1%.

Buccella hannai (Phleger and Parker)

Plate 2, Figures 13, 14

Eponides hannai Phleger and Parker, 1951, Geol. Soc. Amer., Mem. 46, pt. 2, p. 21, pl. 10, figs. 11a, b, 12a, b, 13a, b, 14a, b.

Present at very low frequencies at a few open-gulf stations in the Mississippi Sound area.

Buliminella cf. bassendorfensis Cushman and Parker

Plate 1, Figures 22, 23

Buliminella bassendorfensis Cushman and Parker, 1937, Contr. Cushman Lab. Foram. Res., vol. 13, pt. 1, p. 40, pl. 4, figs. 13a, b.

This species is at approximately half the open-gulf stations in the Mississippi Sound area at frequencies up to 5%. It is also present at some of the sound stations where there is contamination with the open-gulf fauna.

Buliminella elegantissima (d'Orbigny)

Plate 1, Figures 24, 25

Bulimina elegantissima d'Orbigny, 1839, Voy. Amér. Mérid, vol. 5, pt. 5, "Foraminifères," p. 51, pl. 7, figs. 13, 14.

This species is present at more than half the open-gulf stations in the Mississippi Sound area in low frequencies, up to approximately 3% of the fauna. Generally, it is not present in samples nearest the beaches. It is also present at a few stations behind Horn Island and inside Petit Bois Pass.

Cibicidina strattoni (Applin)

Plate 1, Figures 26, 27

Truncatulina americana Cushman var. *strattoni* Applin, 1925, in Applin, Ellisor, and Kniker, Amer. Assoc. Petrol. Geol. Bull., vol. 9, no. 1, p. 99, pl. 3, fig. 3.

Cibicides concentricus Phleger and Parker, 1951 (not *Truncatulina concentrica* Cushman, 1918), Geol. Soc. Amer., Mem. 46, pt. 2, p. 29, pl. 15, figs. 14a, b, 15a, b.

This species is confined to the open gulf in the Mississippi Sound area except at one station behind Horn Island and at five stations behind Petit Bois Island. It is one of the dominant elements of the open-gulf facies constituting up to 50–60% of the fauna and occurs at most open-gulf stations except in the western area.

Discorbis cf. columbiensis Cushman

Plate 1, Figures 28, 29, 31, 32

Discorbis columbiensis Cushman, 1925, Contr. Cushman Lab. Foram. Res., vol. 1, pt. 2, p. 43, pl. 6, figs. 13a–c; Parker, 1952, Bull. Mus. Comp. Zool., vol. 106, no. 9, p. 418, pl. 6, figs. 9a–d.

In the Mississippi Sound area this is one of the most persistent species in the open-gulf facies, occurring at most open-gulf stations in frequencies averaging 5–10% but in places up to 20%. It is also present at a few sound stations where there has been contamination with open-gulf forms.

Discorbis floridana Cushman

Plate 1, Figures 30, 33, 34

Discorbis floridanus Cushman, 1922, Publ. 311, Carnegie Inst. Washington, p. 39, pl. 5, figs. 11, 12.

Present at more than half the open-gulf stations in the Mississippi Sound area in average frequencies of 1–3%.

Elphidium spp.

In the Mississippi Sound area the various species of *Elphidium* have been treated as a unit for the ecological purposes of the present paper. The reasons for this are that the various species appear to behave as an ecological unit. The species are listed here. The *Elphidium* species group constitutes an important element of the open-gulf fauna in the Mississippi Delta area but there is much contamination in the sound back of islands and around passes. The *Elphidium* group commonly makes up a high proportion of the fauna in these locations. It is at more stations in the western part of the open gulf than most types, and extends up to Biloxi Bay.

Elphidium advenum (Cushman)

Plate 1, Figure 36

Polystomella advena Cushman, 1922, Publ. 311, Carnegie Inst. Washington, p. 56, pl. 9, figs. 11, 12.

Elphidium discoidale (d'Orbigny)

Plate 1, Figure 37

Polystomella discoidale d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 56, pl. 6, figs. 23, 24.

Elphidium delicatulum Bermudez

Plate 1, Figure 35

Elphidium delicatulum Bermudez, 1949, Cushman Lab. Foram. Res., Spec. Publ. 25, p. 168, pl. 11, figs. 22, 23.

Elphidium galvestonensis Kornfeld

Plate 2, Figures 1, 2

Elphidium gunteri Cole var. *galvestonensis* Kornfeld (part), 1931, Contr. Dept. Geol. Stanford Univ., vol. 1, no. 3, p. 87, pl. 15, figs. 1a, b. (Not 2a, b, 3a, b.)

Elphidium gunteri Cole

Plate 2, Figures 3, 4

Elphidium gunteri Cole, 1931, Fla. State Geol. Surv. Bull. 6, p. 34, pl. 4, figs. 9, 10.

Elphidium incertum mexicanum Kornfeld

Plate 2, Figures 5, 6

Elphidium incertum (Williamson) var. *mexicanum* Kornfeld, 1931, Contr. Dept. Geol., Stanford Univ., vol. 1, no. 3, p. 89, pl. 16, figs. 1a, b, 2a, b.

Elphidium matagordanum (Kornfeld)

Plate 2, Figure 7

Nonion depressula (Walker and Jacob) var. *matagordana* Kornfeld, 1939, Contr. Dept. Geol. Stanford Univ., vol. 1, no. 3, p. 87, pl. 13, figs. 2a, b.

Elphidium poeyanum (d'Orbigny)

Plate 2, Figures 8, 9

Polystomella poeyana d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 55, pl. 6, figs. 25, 26.

Epistominella vitrea Parker

Plate 2, Figures 11, 12

Epistominella vitrea Parker, 1953, in Parker, Phleger, and Peirson, Cushman Found. Foram. Res., Spec. Publ. No. 2, p. 9, pl. 4, figs. 34–36, 40, 41.

Gaudryina exilis Cushman and Bronnimann

Plate 2, Figure 16

Gaudryina exilis Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 40, pl. 7, figs. 15, 16.

Present at most stations in Mississippi Sound in frequencies averaging 2–10%. It also occurs in the open gulf in this area but at only a few stations and in lower per cents than in the sound facies, generally less than 1%.

Guttulina australia (d'Orbigny)

Plate 2, Figure 15

Globulina australis d'Orbigny, 1839, Voy. Amér. Mérid., vol. 5, pt. 5, "Foraminifères," p. 60, pl. 1, figs. 1–4.

This species occurs at approximately half the open-gulf stations in the Mississippi

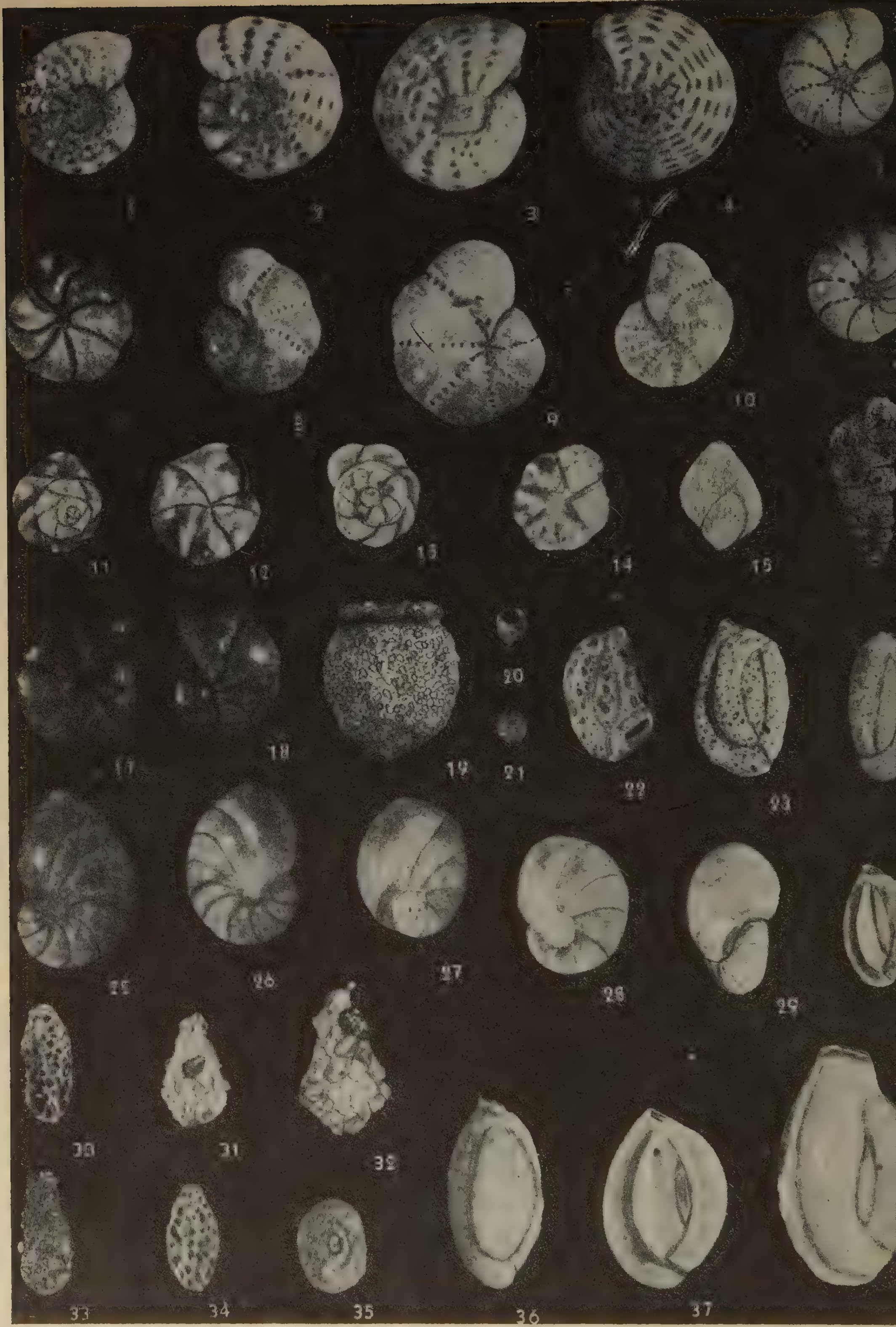

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Plate 2

Sound area, commonly in low frequencies, 1–2%, but in places more. It is present at a few stations in Mississippi Sound where mixed faunas occur.

Haplophragmoides subinvolutum Cushman and McCulloch

Plate 2, Figures 17, 18

Haplophragmoides subinvolutum Cushman and McCulloch, 1939, Allan Hancock Pacific Exped., vol. 6, no. 1, p. 83, pl. 7, figs. 3–5.

Occurs at several marsh stations in the Mississippi Sound area, generally with frequencies less than 5% but in places much higher.

Lagunculina vadescens Cushman and Bronnimann

Plate 2, Figure 19

Lagunculina vadescens Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 1, p. 15, pl. 3, figs. 1, 2.

This species is reported from only one marsh station on Pt. aux Chenes bordering Mississippi Sound.

Leptodermella variabilis Parker

Plate 2, Figures 20, 21

Leptodermella variabilis Parker, 1952, Bull. Mus. Comp. Zool., vol. 106, no. 10, p. 452, pl. 1, figs. 11a, b, 12.

This small and fragile species is very abundant in the series of inner-marsh samples taken west of Graveline Bay where it is 30–60% of the fauna. It also occurs in lower per cents at many other marsh stations in the Mississippi Sound area.

EXPLANATION OF PLATE 2

FIGS.

1, 2. *Elphidium galvestonensis* Kornfeld. 1, ×56; 2, ×75. Miss. Delta Sta. 52.
3, 4. *Elphidium gunteri* Cole. ×56. 3, Miss. Sd. Sta. 1170; 4, Miss. Delta. Sta. 234.
5, 6. *Elphidium incertum mexicanum* Kornfeld. 5, ×56; 6, ×75. 5, Miss. Delta Sta. 9; 6, Miss. Sd. Sta. 974c.
7. *Elphidium matagordanum* (Kornfeld). ×56. Miss. Delta. Sta. 86.
8, 9. *Elphidium poeyanum* (d'Orbigny). ×56. Miss. Delta Sta. 9.
10. *Elphidium translucens* Natland. ×56. Miss. Sd. Sta. 1262.
11, 12. *Epistominella vitrea* Parker. ×75. Miss. Delta. Sta. 72.
13, 14. *Buccella hannai* (Phleger and Parker). ×75. 13, Miss. Sd. Sta. 1248; 14, Miss. Delta Sta. 307.
15. *Guttulina australis* (d'Orbigny). ×48. Miss. Sd. Sta. 984.
16. *Gaudryina exilis* Cushman and Bronnimann. ×56. Miss. Delta Sta. 78.
17, 18. *Haplophragmoides subinvolutum* Cushman and McCulloch. ×48. Miss. Sd. Sta. 969.
19. *Lagunculina vadescens* Cushman and Bronnimann. ×56. Miss. Sd. Sta. 1028.
20, 21. *Leptodermella variabilis* Parker. ×48. Miss. Sd. Sta. 968.
22, 23. *Miliammina fusca* (H. B. Brady). 22, ×75; 23, ×56. Miss. Sd. Sta. 969.
24. *Miliammina* sp. ×56. Miss. Delta Sta. 234.
25, 26. *Nonionella atlantica* Cushman. ×75. Miss. Sd. Sta. 1228.
27–29. *Nonionella opima* Cushman. ×75. 27, Miss. Delta Sta. 75; 28, 29, Miss. Sd. Sta. 1265.
30. *Nouria polymorphinoides* Heron-Allen and Earland. ×56. Miss. Delta Sta. 71.
31, 32. *Proteonina atlantica* Cushman. ×58. Miss. Delta. Sta. 71.
33. *Proteonina lagenaria* (Berthelin). ×56. Miss. Sd. Sta. 1020c.
34, 35. "*Proteonina*" sp. 34, ×48; 35, ×75. Miss. Sd. Sta. 992.
36. *Quinqueloculina* cf. *compta* Cushman. ×56. Miss. Delta Sta. 69.
37. *Quinqueloculina* sp. ×56. Miss. Delta Sta. 90.
38. *Quinqueloculina cultrata* (H. B. Brady). ×56. Miss. Delta Sta. 37.
39. *Quinqueloculina* cf. *funafutiensis* (Chapman). ×56. Miss. Delta Sta. 9.

Miliammina fusca (H. B. Brady)

Plate 2, Figures 22, 23

Quinqueloculina fusca H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 47 (286), pl. 11, figs. 2a–c, 3.

In the Mississippi Sound area this species is characteristic of both the marsh and the estuary facies. It is the dominant species in these environments in most samples, averaging 30–50% of the faunas. It is present at every station on Isle aux Herbes and at three stations on Horn Island. It occurs in a fringe-like distribution in Mississippi Sound bordering the mainland and the eastern island marshes. It is not present in lower Mississippi Sound, except in the east, and not present in the open gulf.

Miliammina sp.

Plate 2, Figure 24

Miliammina sp., 1953, Parker, Phleger, and Peirson, Cushman Found. Foram. Res., Spec. Publ. No. 2, p. 11, pl. 1, figs. 42, 43.

This form appears to be distinct from *Miliammina fusca* but was not differentiated from that species in the plots of geographic distribution.

Miliolidae

Various species of the Miliolidae, if considered as a unit, are one of the dominant elements of the open-gulf assemblage in the Mississippi Sound area, often being 10–20% or more of the open-gulf assemblage. They are confined to outside the islands and occur in the sound only where open-gulf and sound faunas are mixed. In the western open gulf these forms are only present south of Ship Island.

There are several species included in this group and no attempt was made to differentiate them in the Mississippi Sound area. They appear to behave as an ecologic unit, although it is possible that more detailed study may show slight differences of distribution. Some of the more common species are illustrated in the plates.

Nonionella atlantica Cushman

Plate 2, Figures 25, 26

Nonionella atlantica Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 90, pl. 20, figs. 4, 5.

This species is confined to the open-gulf facies in the Mississippi Sound area where it averages 5–10% of the population and in places more. It is present in areas of mixing in the lowermost sound area.

There has been some confusion about the separation of *Nonionella atlantica* and *N. opima* during the population analyses of the Mississippi Sound samples, so that many *N. opima* are probably included in the frequencies of *N. atlantica*. It is apparent that these two species have the same ecologic distribution in this area and can be considered as a unit. It was not believed necessary, therefore, to check these identifications.

Nonionella opima Cushman

Plate 2, Figures 27–29

Nonionella opima Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 90, pl. 20, figs. 1–3.

This species is confined to the open-gulf facies in the Mississippi Sound area. It appears probable that many of the specimens identified as *N. atlantica* should be included here.

Nouria polymorphinoides Heron-Allen and Earland
Plate 2, Figure 30

Nouria polymorphinoides Heron-Allen and Earland, 1914, Trans. Zool. Soc. London, vol. 20, pt. 12, p. 376, pl. 37, figs. 1–15.

Proteonina comprima Phleger and Parker, 1951, Geol. Soc. Amer., Mem. 46, pt. 2, p. 2, pl. 1, figs. 1–3.

This species is not listed in the counts but here and there specimens are present in the open-gulf facies in the Mississippi Sound area.

Proteonina atlantica Cushman
Plate 2, Figures 31, 32

Proteonina atlantica Cushman, 1944, Cushman Lab. Foram. Res., Spec. Publ. 12, p. 5, pl. 1, Fig. 4.

Recognized at a few open-gulf stations in the Mississippi Sound area where it is in very low frequency.

Proteonina lagenaria (Berthelin)
Plate 2, Figure 33

Haplophragmium lagenarium Berthelin, 1880, Mém. Soc. Géol. France, ser. 3, vol. 1, no. 5 p. 21, pl. 4, figs. 2a, b.

In the Mississippi Sound area this species is reported from the marsh from six stations at less than 1%. It is also reported from a few stations in the open-gulf facies, but these specimens may belong to a different species.

Quinqueloculina cf. comptà Cushman
Plate 2, Figure 36

Quinqueloculina compta Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 87, pl. 19, fig. 2.

Quinqueloculina cultrata (H. B. Brady)
Plate 2, Figure 38

Miliolina cultrata H. B. Brady, 1881, Quart Journ. Micr. Sci., vol. 21, p. 45; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 161, pl. 5, figs. 1, 2.

Quinqueloculina cf. funafutiensis (Chapman)
Plate 2, Figure 39

Miliolina funafutiensis Chapman, 1900, Journ. Linn. Soc. Zool., vol. 28, p. 178, pl. 19, fig. 6.

Recurvoides sp.
Plate 3, Figures 1, 2

Recurvoides sp., Parker, Phleger, and Peirson, 1953, Cushman Found. Foram. Res., Spec. Publ. No 2, p. 13, pl. 1, figs. 31, 32.

This species occurs at several Mississippi Sound area marsh stations in low frequencies.

Reussella atlantica Cushman
Plate 3, Figure 3

Reussella spinulosa (Reuss) var. *atlantica* Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 91, pl. 20, figs. 6, 7.

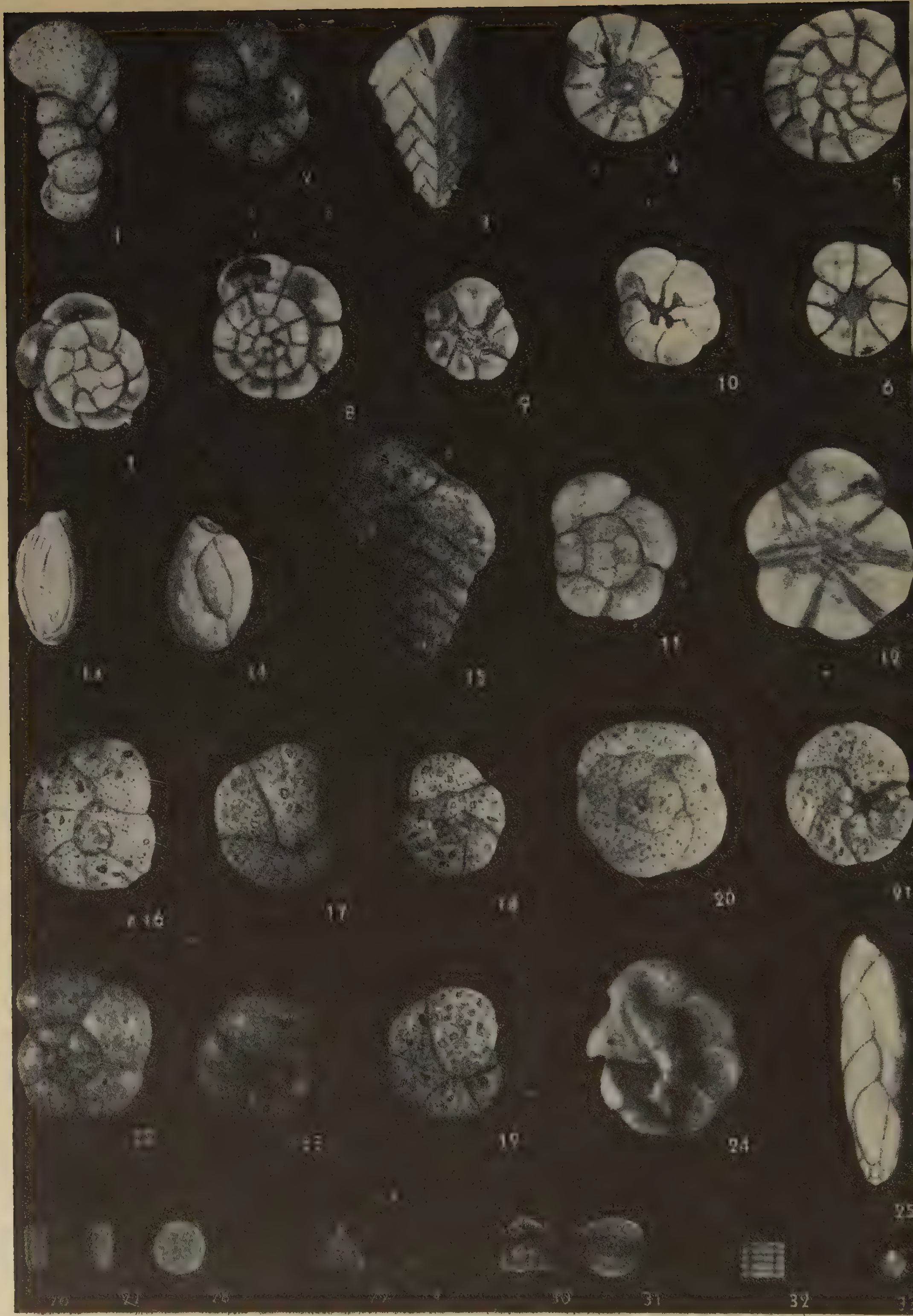
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PLATE 3

This species occurs at a few open-gulf stations in the Mississippi Sound area in low frequencies.

"Rotalia" beccarii (Linné) variants

Plate 3, Figures 4–10

Nautilus beccarii Linné, 1758, Syst. Nat., Ed. 10, p. 710.
"Rotalia" beccarii variants A, B, C, 1953, Parker, Phleger, and Peirson, Cushman Found. Foram. Res., Spec. Publ. No. 2, p. 13, pl. 4, figs. 20–22, 25–30.

At least two, and possibly more, variants are included here since they appear to have a similar distribution.

This species is one of the two most abundant open-gulf species in the Mississippi Sound area, occurring at essentially all open-gulf stations with average frequencies of 10–30%. It occurs in the sound where the open-gulf and sound faunas are mixed.

"Rotalia" rolshauseni Cushman and Bermudez

Plate 3, Figures 11, 12

Rotalia rolshauseni Cushman and Bermudez, 1946, Contr. Cushman Lab. Foram. Res., vol. 22, pt. 4, p. 119, pl. 19, figs. 11–13.

Present at a few open-gulf Mississippi Sound area stations in low frequencies.

Textularia cf. mayori Cushman

Plate 3, Figure 15

Textularia mayori Cushman, 1922, Publ. 311, Carnegie Inst. Washington, p. 23, pl. 2, fig. 3.

In the Mississippi Sound area this species is present at a few open-gulf stations in low frequencies, usually less than 1%.

EXPLANATION OF PLATE 3

FIGS.

1, 2. *Recurvoides* sp. 1, ×56; 2, ×48. Miss. Sd. Sta. 968.
3. *Reussella atlantica* Cushman. ×75. Miss. Sd. Sta. 974.
4–6. *"Rotalia" beccarii* var. (Linné). 4, 5, ×56; 6, ×75. 4, 5, Miss. Delta Sta. 52; 6, Miss. Sd. Sta. 1264.
7–10. *"Rotalia" beccarii* var. (Linné). 7–9, ×75. 10, ×56. Miss. Delta Sta. 9.
11, 12. *"Rotalia" rolshauseni* Cushman and Bermudez. 11, ×75; 12, ×48. Miss. Delta Sta. 70.
13. *Spiroloculina* cf. *antillarum* d'Orbigny. ×75. Miss. Sd. Sta. 1228.
14. *Triloculina sidebottomi* (Martinotti). ×56. Miss. Delta Sta. 9.
15. *Textularia* cf. *mayori* Cushman. ×48. Miss. Sd. Sta. 1228.
16–19. *Trochammina* cf. *laevigata* Cushman and Bronnimann. ×75. 16, 17, Miss. Delta Sta. 138; 18, 19, Miss. Delta Sta. 183.
20, 21. *Trochammina comprimata* Cushman and Bronnimann. ×56. Miss. Sd. Sta. 1014.
22, 23. *Trochammina inflata* (Montagu). ×48. Miss. Sd. Sta. 969.
24. *Trochammina macrescens* H. B. Brady. ×75. Miss. Sd. Sta. 995.
25. *Virgulina pontoni* Cushman. ×75. Miss. Sd. Sta. 1228.
26–28. *Coscinodiscus* sp. ×48. Miss. Sd. Sta. 1284.
29. *Triceratum* sp. ×48. Miss. Sd. Sta. 1406.
30, 31. Diatom 1. ×48. Miss. Sd. Sta. 1100.
32. Diatom 3. ×48. Miss. Sd. Sta. 1200.
33. Diatom 2. ×48. Miss. Sd. Sta. 1184.

Triloculina sidebottomi (Martinotti)

Plate 3, Figure 14

Miliolina subrotunda Sidebottom, 1904 (not *Verniculum subrotundum* Montagu, 1803), Manchester Lit. Phil. Soc., vol. 68, no. 5, p. 8, text fig. 2, pl. 3, figs. 1–7.

Trochammina comprimata Cushman and Bronnimann

Plate 3, Figures 20, 21

Trochammina comprimata Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 41, pl. 8, figs. 1–3.

This species is a marsh form in the Mississippi Sound area, occurring at numerous marsh stations in variable frequencies. It occurs in near-by streams where they are narrow and there is apparent contamination from the marsh.

Trochammina inflata (Montagu)

Plate 3, Figures 22, 23

Nautilus inflatus Montagu, 1808, Test. Brit., p. 81, pl. 18, fig. 3.

This species occurs at several marsh stations in the Mississippi Sound area with frequencies generally low, but in places as high as 15%. It is generally not present in the estuaries.

Trochammina cf. laevigata Cushman and Bronnimann

Plate 3, Figures 16–19

Trochammina laevigata Cushman and Bronnimann, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 41, pl. 8, figs. 1–3.

This species is reported from a few stations in the sound and open gulf in low frequencies in the Mississippi Sound area.

Trochammina macrescens H. B. Brady

Plate 3, Figure 24

Trochammina inflata (Montagu) var. *macrescens* H. B. Brady, 1870, Ann. Mag. Nat. Hist., ser. 4, vol. 6, p. 51, pl. 11, figs. 5a–c.

This is a marsh species which occurs in low frequencies at a large number of marsh stations in the Mississippi Sound area. It is present in very few estuary samples.

Urnulina

Urnulina occurs only in the inner part of the Mississippi Sound area marsh in the Graveline Bay marsh where it is up to 75% of the fauna. It also occurs in the upper Pascagoula River marsh.

There probably are several species included here. No attempt was made to separate them because of their probable limited usefulness for geological purposes.

Virgulina pontoni Cushman

Plate 3, Figure 25

Virgulina pontoni Cushman, 1932, Contr. Cushman Lab. Foram. Res., vol. 8, pt. 1, p. 17, pl. 3, fig. 7.

This species is a minor constituent of the Mississippi Sound area open-gulf fauna, occurring at several stations at 1% or less of the population.

ADDENDUM

Recent work on the living Foraminifera in a few additional samples from Mississippi Sound has shown that the open-gulf species appear to be somewhat more extensive within the sound than reported in this paper. This new information was obtained while the present paper was in press. Specifically, the mixed, open-gulf and sound fauna is rather widespread in the outer half of Mississippi Sound, and there are occasional low frequencies of open-gulf forms at a few places near the mainland. Additional samples south of Biloxi Bay contain a relatively high percentage of open-gulf forms and this tends to confirm this feature of the distribution. The new data confirm the conclusion that the *Ammobaculites* fauna is dominant in Mississippi Sound and at most stations composes most or all of the Foraminifera.

Open-gulf, calcareous species were destroyed in some samples due to the preservation of the sediment in a solution of formaldehyde. While the formaldehyde had been made basic by the addition of sodium carbonate, it was only recently realized that formaldehyde continuously breaks down to form formic acid and that considerable excess of base must be added to such a solution. Solution of calcareous tests in the samples appears to have been related to the amount of calcium carbonate in the sediment. A relatively high percentage of calcium carbonate assists in neutralizing the formic acid being produced. In many Mississippi Sound samples essentially all the calcium carbonate is in the form of foraminiferal tests. Where there are relatively few Foraminifera they tend to be dissolved in such samples and where they are abundant they may buffer the solution.

The total effect has been to somewhat accentuate the differences between the open-gulf and the sound faunas. It is the opinion of the author that the usefulness of the generalizations and hypotheses presented is not impaired.

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(Not available for distribution.)

Deep-Sea Research, 1954, Vol. 1, pp. 170 to 175. Pergamon Press Ltd., London.

The age of the sediment collected at *Challenger* (1875) Station 225 and the distribution of *Ethmodiscus rex* (Rattray)

WILLIAM R. RIEDEL*

Summary—The sediment sample collected by H.M.S. *Challenger* in 1875 at her Station 225 is shown to be from an outcrop of Middle Tertiary age. Therefore the presence of the diatom *Ethmodiscus rex* (Rattray) in this sediment sample is not the result of its having lived in the overlying waters in Recent geological time. In two other recorded occurrences, this diatom is believed to be associated with other sedimentary constituents which are, at least in part, of Tertiary age. Five of the Radiolaria occurring at *Challenger* Station 225 are discussed briefly.

THE SEDIMENT SAMPLE FROM *CHALLENGER* (1875) STATION 225

IN a discussion of the distribution of the large diatom *Ethmodiscus rex* (Rattray), WISEMAN & HENDEY (1953) record its occurrence in the sediment collected at Station 225 of the original *Challenger* expedition (at 11°24·0′N 143°16·0′E; depth 4475 fm). This has brought into added prominence a question which has interested the author for some time – namely, what is the age of this sample of radiolarian ooze ? Many of the 140 species of Radiolaria which HAECKEL (1887) mentions as occurring at this station are strikingly different from those found in most other Pacific sediments. Recent examination of deep-sea sediments collected in the Pacific by the Swedish Deep-Sea Expedition and by various American expeditions has indicated that outcrops of Tertiary sediment occur not infrequently on the floor of the deep ocean, and that, in many other localities, reworked Tertiary microfossils are mixed with the Recent sediment at the surface of the sea floor. If the sediment at *Challenger* Station 225 is Tertiary in age, the occurrence of *Ethmodiscus rex* at that locality has little bearing on the present-day distribution of that diatom.

Dr. J. D. H. WISEMAN, of the British Museum (Natural History), has kindly sent the author small portions from three different places in the short core obtained at Station 225, and examination of the Radiolaria in these samples (Brit. Mus. (Nat. Hist.), Reg. No. M289) shows that none of the forms which are abundant in purely Recent Pacific sediments are present. Thus it is probable that the sediment is purely Tertiary in age, and comparison of the contained Radiolaria with assemblages of known Tertiary ages should enable us to date the fauna approximately. The dating of Tertiary sediments on the basis of the Radiolaria which they contain is one of the least-developed facets of micropalaeontology, but the following comments on the distribution of a few of the more abundant and characteristic species occurring at Station 225 indicate that an approximate age can be assigned to the sediment. Although the five species discussed below represent only a small fraction of the total number present, they are considered to be sufficient for an approximate age assignment – a more complete discussion of the species in this sample must await a thorough reconsideration of all the *Challenger* Radiolaria from a descriptive and taxonomic point of view. The radiolarian assemblage shows practically no variation in the three

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* Contribution from the Scripps Institution of Oceanography, new series, no. 696.

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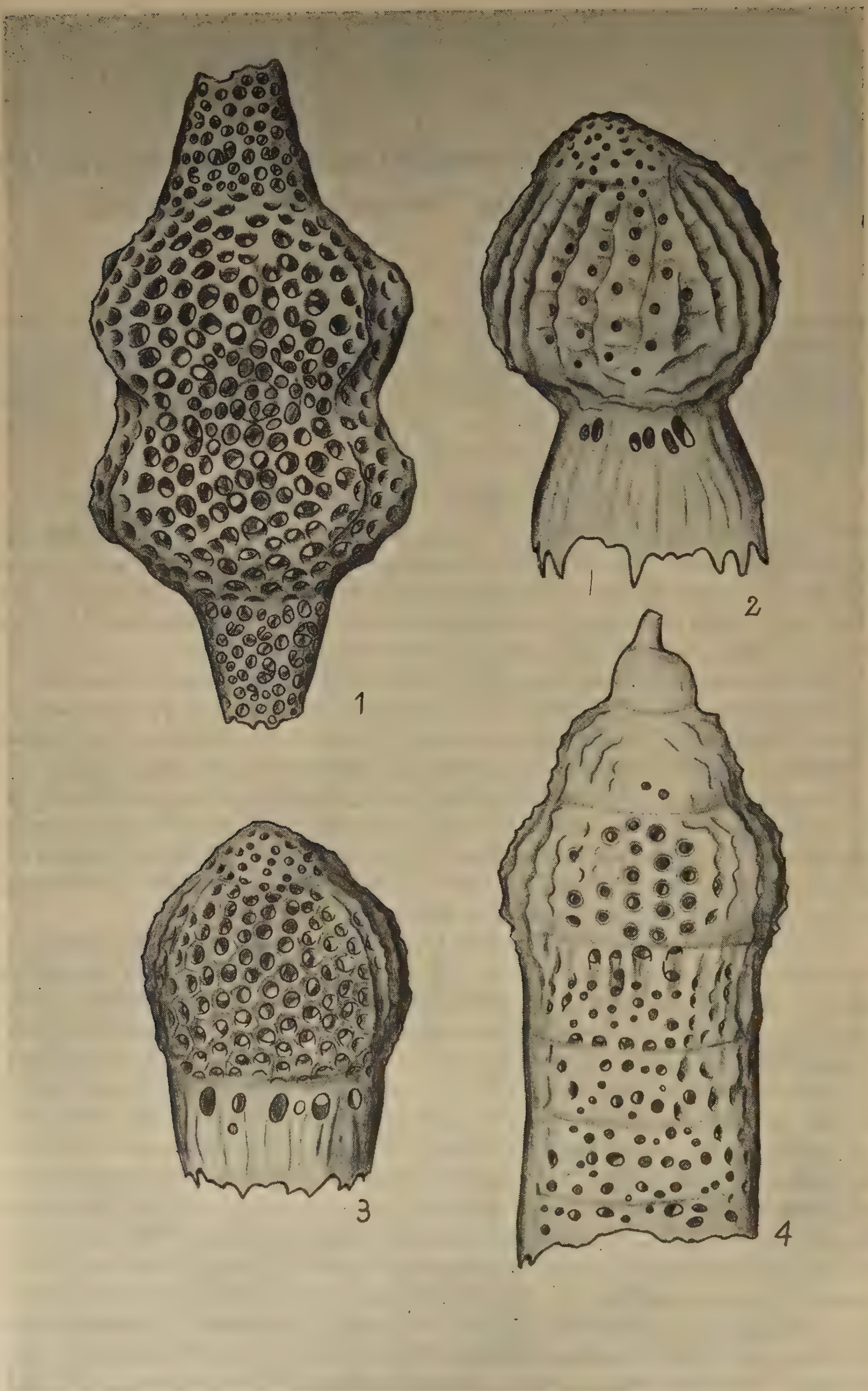

Plate I. Radiolaria from *Challenger* (1875) Station 225, all x 475.
Fig. 1. *Cannartidium ? mammiferum* Haeckel. Figs. 2, 3. *Cycladophora favosa* Haeckel.
Fig. 4. *Stichocorys ? wolffii* Haeckel.

samples examined; each of the Radiolaria listed below was found in all three samples.

Cannartidium ? mammiferum Haeckel.—The systematic classification of the members of HAECKEL's families Artiscida, Cyphinida, Panartida and Zygartida (which together comprise the " family Artiscidae Haeckel emend." of DEFLANDRE, 1953, pp. 416 and 418) is at present very unsatisfactory. Before the taxonomy can be revised, it will be necessary to re-examine all of the species concerned from their type localities. Preliminary investigations indicate, however, that some members of these families underwent rapid evolution during the Tertiary, and that they may therefore prove especially useful for age determinations. The form (Pl. 1, fig. 1) which is here tentatively identified as *Cannartidium mammiferum* Haeckel has less regular fenestrated protuberances on the cortical shell than shown in HAECKEL's figure, and the polar projections are often spongy rather than tubular; these differences are probably not of great taxonomic significance, and the form which occurs at *Challenger* Station 225 appears to be identical with, or very closely related to, the form which HAECKEL described under this name from *Challenger* Station 268. Specimens similar to those occurring at *Challenger* Station 225 have been found in many sediments of Middle Tertiary age, including the " Moronitas " (Burdigalian) of Muro, Mallorca (see COLOM & GAMUNDI, 1951); the Cipero formation (Upper Oligocene of CUSHMAN & STAINFORTH, 1945) at Retrench Quarry and Golconda Estate, Trinidad;* and in the Upper Oligocene or Lower Miocene siliceous clay of the islet off the NE corner of Colebrooke Island, Andaman Islands* (see JACOB & SHRIVASTAVA, 1952).

Tympanidium binoctonum Haeckel.—This species, of which *Challenger* Station 225 is the type locality, has been found in many Middle Tertiary sediments, in both subaerial and submarine localities. It occurs, for example, in the Oligocene chalky marl of the sea cliff along the highway, ½ mile SE of the plaza in Jeremie, Haiti; in the Cipero formation (Upper Oligocene) at Golconda Estate, Trinidad; in the Upper Oligocene or Lower Miocene siliceous clay of the islet off the NE corner of Colebrooke Island, Andaman Islands; and in the sediment at *Challenger* (1875) Station 268, which is suspected to be Upper Oligocene in age.

Cycladophora favosa Haeckel.—This species, of which *Challenger* Station 225 is the type locality, is rather difficult to identify. Specimens found by the present author usually have less pores on the post-thoracic part of the shell (Pl. 1, figs. 2 and 3), and thus approach the description of *Carpocanium palmipes* Haeckel, which was also described from this Station. However, HAECKEL's two figures of *Cycladophora favosa* indicate that the structure of the post-thorax is variable, and that the range of variation is probably sufficient to include the examples figured in this paper. This species has been found in the Oligocene chalky marl of the sea cliff along the highway, ½ mile SE of the plaza in Jeremie, Haiti; in the Cipero formation (Upper Oligocene) at Retrench Quarry and Golconda Estate, Trinidad; in the Upper Oligocene or Lower Miocene siliceous clay of the islet off the NE corner of Colebrooke Island, Andaman Islands; and in the (probably Upper Oligocene) sediment at *Challenger* (1875) Station 268.

Calocyclas virginis Haeckel.—*Challenger* Station 225 is the type locality of this species. It occurs also in the Cipero formation (Upper Oligocene) at Retrench Quarry and Golconda Estate, Trinidad; in the Upper Oligocene or Lower Miocene siliceous clay of the islet off the NE corner of Colebrooke Island, Andaman Islands; and in the (probably Upper Oligocene) sediment at *Challenger* (1875) Station 268.

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* TEMPÈRE & PERAGALLO (1907, p. 459) report " *Coscinodiscus rex* Wall." as occurring fossil in unspecified marine sediments of Trinidad. Fragments of large diatoms which in many respects resembly *Ethmodiscus rex* (Rattray) occur in the Cipero Formation of Trinidad and in the Middle Tertiary of the Andaman Islands, but the present author has been unable to confirm their identity with that species.

Stichocorys ? wolffii Haeckel.—The abundant species of *Stichocorys* in this sample, and the one to which the name *S. wolffii* probably belongs, does not agree very well with HAECKEL's description and figure of that species. The cephalis and thorax usually have less pores than shown in HAECKEL's figure, and the longitudinal ridges on the thorax are usually less pronounced. The difference in the widths of the third and fourth segments is generally less than indicated by HAECKEL, and the post-abdominal segments are often more similar to those of his figure of *S. baerii* than to those of his figure of *S. wolffii*. A typical specimen is figured on Pl. 1, fig. 4. A species of *Stichocorys* closely resembling the form figured occurs in the Cipero formation (Upper Oligocene) at Retrench Quarry, Trinidad. *S. wolffii* occurs in the sediment at *Challenger* (1875) Station 268 (probably Upper Oligocene).

It will be seen from the above comments that the Radiolaria in the sediment from *Challenger* Station 225 indicate that the sample was taken from an outcrop of Middle Tertiary age (probably Upper Oligocene or Lower Miocene). Apart from the absence of the Radiolaria comprising the present-day Pacific fauna, and the presence of Middle Tertiary species, there is a certain amount of other evidence which seems to support the conclusion that the sediment sample is from a Tertiary outcrop. MURRAY & RENARD (1891, p. 204) state, of this sounding:- " The tube had sunk fully three inches into the deposit; the upper layers were of a red colour, and contained much more peroxide of manganese than the lower ones, which were of a pale yellow or straw colour . . . " The relative abundance of manganese dioxide in the upper layers of the sediment probably indicates a long period of very slow deposition, or non-deposition, during at least part of the time since the lighter-coloured lower layers were deposited. Also, the fact that " the whole of the lower part of the deposit when it came up had a very compact and laminated appearance," and that " it was difficult to separate the various components of the deposit the one from the other by shaking the whole in a bottle with water," may be taken to indicate that diagenetic changes of a low order had resulted in the solution of some of the organic silica, which was then re-deposited to form a cement which loosely bound the other constituents of the sediment; such low-grade lithification might be expected more commonly in Tertiary than in Recent deep-sea sediments.

SAMPLES OF *ETHMODISCUS* OOZE COLLECTED BY H.I.J.M.S. *KOSYU* IN 1933

HANZAWA (1933) and WISEMAN & HENDEY (1953) list the localities 9°21·0′N 146°50·0′E and 8°04·0′N 142°15·0′E as being included within the area of distribution of *Ethmodiscus* ooze, because the *Kosyu* obtained samples of that sediment at those localities in 1933. Here again the age of the sediment samples is an interesting problem, and it is not impossible that the *Ethmodiscus* frustules were deposited during the Tertiary. Two figures of one of these samples (HANZAWA, 1933, pl. 1, fig. 2; pl. 2, fig. 2) show considerable numbers of discoasters, and discoasters are mentioned in the description of the other sample (9°21′N 146°50′E): these microfossils can perhaps be used to date the sediment. Dr. M. N. BRAMLETTE and the present author are preparing a paper on the stratigraphic value of the discoasters, and our investigations have revealed two points which have a bearing on the sediment samples under consideration. Firstly, the organisms which produced discoasters apparently lived only during the Tertiary. Secondly, the types of discoasters shown in HANZAWA's figures are restricted to the Upper Tertiary. Thus the sediment sample from 9°21′N 146°50′E is at least partly composed of pre-Recent material, and the sample from 8°04′N 142°15′E is partly or completely Upper Tertiary in age. Whether either or both of these samples were obtained from Tertiary outcrops, and whether the *Ethmodiscus* frustules were deposited during Tertiary or Recent time, could perhaps be determined by a more complete micropalaeontological examination of the original samples.

CONCLUSIONS

There is little doubt that the sediment obtained at *Challenger* Station 225 is from an outcrop of Middle Tertiary radiolarian ooze. The occurrence of *Ethmodiscus rex* in this sediment has no connection with its existence in the overlying waters at the present day, but rather means that the diatom lived in that region during Middle Tertiary time. Tertiary sediment is apparently present at two of the localities at which HANZAWA reported *Ethmodiscus* ooze, but the data at present available are not sufficient to indicate whether these two sediment samples are purely Tertiary, or mixtures of material of different ages. Thus the occurrence of *Ethmodiscus* in these two samples obtained by the *Kosyu* may result either from the existence of the diatom in the area during the Tertiary, or from its living there during Recent time.

Neither HANZAWA nor WISEMAN & HENDEY state that they believe that the frustules of *Ethmodiscus* in these three sediment samples have been formed and deposited during Recent geological time. Until recently, it has generally been assumed that practically all of the constituents of the sediments at the surface of the sea floor are of Recent origin. Investigations carried out during the last few years have indicated that this assumption is often invalid, at least in the tropical Pacific Ocean, and that a sediment which does not contain reworked, heterochthonous elements may be the exception rather than the rule. It has therefore become very important to consider the factor of time in all studies relating to deep-sea sediments. Our present knowledge of the palaeontology of many types of planktonic organisms is insufficient for their effective use in dating sediments, but their usefulness will doubtless increase rapidly with the expansion of deep-sea research. The planktonic Foraminifera can already be used for this purpose, and recent advances in our knowledge of the Tertiary Radiolaria, silicoflagellates, coccoliths and discoasters indicate that all of these groups of fossils may soon be employed in the determination of the ages of pelagic sediments.

Finally, it may be pointed out that many of the difficulties which attend research on Recent and Tertiary Radiolaria stem from fundamental faults in HAECKEL's classification of these organisms, and from the inadequacy of his species descriptions. Examples of these difficulties are to be found among even the small number of species mentioned earlier in this paper. A large proportion of all known Radiolaria were originally described by HAECKEL from the sediments collected by the *Challenger* expedition of 1873-76. In order to resolve these difficulties, therefore, it is necessary thoroughly to restudy the forms in the orginal samples. Because of the foresight of the authorities of the Challenger Office and of the British Museum (Natural

History), portions of the *Challenger* samples have been preserved for almost a century, thus making possible the re-examination of this invaluable material.

The results included in this paper represent part of the author's research carried out during a visit to the U.S.A. which was made possible by the award of a John Murray Travelling Studentship in Oceanography and Limnology.

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SCIENCE LOOKS INTO IT

Calving of the California Grays

Raymond M. Gilmore & Gifford Ewing

THINGS we are sure of that turn out to be happily untrue add spice to the life of a scientist. We have recently had the fun of uncovering a fallacy in the well-publicized natural history of the California gray whale.

During the past century the annual parade of these enormous mammals, along the coast and past the headlands of southern California, has excited the interest and curiosity of casual shore watchers and conservationists alike. Indeed, before the days of the '49ers it was the gray whale that brought ships from New England around the Horn to the coast of California.

The animal has twice survived near extinction at the hands of whalers but has recovered each time, and now is annually seen in large numbers swimming close to shore, seeking shelter in lagoons and bays, in a migration that terminates in the desolate inland waterways of the Baja California desert. It is in these quiet waters, sometimes 20 or 30 miles from the open sea, that the cows give birth to their 12-foot calves and it is in these waters that the annual remating takes place.

After much patient study it had generally been agreed that the breeding range of the species was limited to a half dozen locations along the middle one-third of the Pacific coast of the peninsula and it was believed that the maximum population which could be supported was that which would fully exploit the restricted nurseries in this area. Although occasional stragglers were reported from other areas, little thought was given to the possible discovery of additional calving grounds, and the limits of the known breeding range have not been significantly extended since the mid-1800's.

Recently, however, we have had the good luck to find gray whales calving in small numbers in two entirely new locations on the eastern side of the Gulf of California along the coast of Sonora and Sinaloa, some 350 miles beyond the most southerly heretofore recorded nursery.

Seven years of study begun by Dr. Carl L. Hubbs of the Scripps Institution of Oceanography and pursued by him and by many coöperating scientists including ourselves, have involved ships, skiffs, dug-outs, aircraft and helicopters, as well as the examination of historic records and interviews with local fishermen. Insofar as these studies defined the breeding range of the gray whale, they may be summarized as follows:

San Diego and probably adjacent *Mission Bay* — once heavily populated, but now no longer entered, probably on account of the heavy boat traffic. In an earlier day the ladies of San Diego dared not be rowed across the bay to their favorite picnic site on North Island, because of the prevalence of gray whales spouting in the harbor.

Bahía de Todos Santos, with its Mexican city of Ensenada—now visited by occasional stragglers which do not stay to calve.

Bahía San Quintín — the situation is similar to that at Bahía de Todos Santos.

Bahía de Sebastian Vizcaíno—heaviest concentration of whales during the breeding season. From the southeast margin of this bay, *Laguna Scammon* and *Laguna Guerrero Negro* (Black Warrior) extend deeply into the Vizcaíno Desert, and these lagoons are now the largest and most important calving nurseries.

Bahía Ballenas — extends into *Laguna de San Ignacio* which also is heavily populated.

Estero — just north of Bahía Magdalena; three entrances, *Boca Las Animas* at the north end, *Boca Santo Domingo* in the middle and *Boca Soledad* at the south; well populated, especially south of Boca Soledad.

Bahía de la Magdalena — a huge bay, perhaps once the most important of the calving and mating areas of the gray whale, now thinly populated, probably because of the rather heavy fishing traffic.

Bahía de Almejas—just south of and connected with Bahia Magdalena; well populated. Until recently this was thought to be the southernmost nursery.

This sums up the known winter range of the California gray whale. So far as the writers are aware, none of the lagoons north of Mission Bay have ever been frequented by calving grays within historic times, despite the apparent suitability of such protected bodies of water as Newport Bay, Anaheim Bay, San Pedro Bay, Morro Bay and especially San Francisco, Bolinas, Tomales and Humboldt bays.

To be sure, apparent stragglers have been reported from time to time in odd places, as for example the three cows with small calves which Hubbs saw on the northwest side of Isla Guadalupe on February 3, 1950. The small size of the calves makes it probable they had been born here some 250 miles offshore from their nearest known regular nursery in Scammon Lagoon.

Nevertheless, as our studies progressed from year to year certain facts began to emerge which caused us to wonder whether there might not be at least one other nursery not known to us. For one thing Charles Scammon,[*] the famous whaler and chronicler of the gray whale, had written somewhat ambiguously that the gray whale never extended its migration south of 20° north latitude, but he nowhere stated categorically that whales were found this far south, nor said whether they were seen along the coast or far out at sea. We presumed he referred to accidental encounters, else more would have been known of these southern migrators. Nevertheless, such a southern limit was 3° or approximately 180 nautical miles south of the tip of Baja California, opposite Cabo Corrientes in the Mexican state of Jalisco.

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[*] *The marine mammals of the north-western coast of North America,* San Francisco and New York. 1874. 319 pp., 37 pls. (page 22).

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While we flew in a small land plane twice in early 1953 for long hours along the desolate, sunbaked, uninhabited and rugged coast line of Baja California, Ewing was happily engrossed in piloting the plane, while Gilmore had time to contemplate Scammon's cryptic remark. The annual census taken by Hubbs had shown that the population was definitely increasing as a result of the complete protection from hunting provided by the International Whaling Convention of 1937, and the successive annual flying census had shown a steady southward push of the population with an increasing number of stragglers scattered along the coast as far south as Cape San Lucas.

On February 3, 1953, Ewing and Andreas Rechnitzer saw a cow and calf just within the Cape near San Jose del Cabo; and along the Pacific Coast between the Cape and Bahía de Almejas they counted 78 gray whales, including two calves. On February 27, 1953, Ewing and Gilmore again saw a cow and calf near San Jose. We wondered what so large a number of gray whales were doing so far south of the southernmost established nursery at Almejas.

Was this the restless wandering of the adolescents and other nonbreeders or were these adults probing for new calving grounds, or perhaps returning from nurseries not yet known? Three times Ewing and Hubbs, Ewing and Rechnitzer, and Ewing and Gilmore reconnoitered the east coast of the peninsula, with negative results. The whales did not seem ever to enter the Gulf proper. The small number of calves among those seen south of Almejas, and the well established restriction of the calving grounds to points much farther north, prompted Gilmore to conclude that these southern individuals were indeed stragglers, aimlessly passing the time before the northward migration began. Nevertheless the air map showed many coastal lagoons and bays on the eastern side of the Gulf, along the coast of Sonora and Sinaloa, the configuration of which aroused our curiosity and kindled our resolve to explore them during the winter of 1953-1954.

Our break came in early January, 1954, during the course of a flight made along the eastern shore of the Gulf by Ewing in company with Dr. Robert Menzies, a staff member at the Scripps Institution of Oceanography, the object of which was the collection of marine isopods and a study of the distribution of the common marine borer Limnoria.

While Menzies was busy hacking in wood structures for Limnoria, Ewing stayed with the float plane which, because of its unfamiliarity, attracted large crowds from the isolated fishing villages along the way. With his very limited Spanish Ewing asked the local fishermen about whales, but got only one bite. In a lagoon, midway between Mazatlán and Topolobampo, one village patriarch remembered seeing whales and calves in years gone by. He thought perhaps they still came in to Bahía de la Reforma, the next lagoon to the north. He told of mothers that spent the winter with their calves, arriving in early February and leaving in April, and of how these mothers would place themselves between their babies and the vicious *bufeos* (killer whales). He could not say whether these whales were similar to the ones found in Baja California *because he had never been on that side of the Gulf.* Shortage of gasoline kept Ewing and Menzies from a systematic search of Bahía de la Reforma, but during a single pass over the bay Menzies spotted one lone whale that seemed to share our astonishment at the encounter, for it stuck its head straight up out of the water in a "spy-hop" typical of the gray whale.

Shortly thereafter, in early February, Gilmore and Ewing made a similar flight in the same plane expressly to look for gray whales and land on the water in all likely lagoons and bays to query fishermen about the whales and any pertinent past history which might throw light on the quest.

Much to our surprise and pleasure we actually saw and counted 44 gray whales, of which 26 were adults and 18 calves, meaning that at least 18 of the adults were cows. They were found in the following places:

		Adult	*Calf*
1 Feb.:	Punta Final, northwest side of Gulf, just north of Bahía de Los Angeles. Probably a stray adult	1	
3 Feb.:	Bay off Puerto Yavaros, just north of Topolobampo, 26° 40′ N.	7	6
3 Feb.:	Bahía de la Reforma (B. Santa Maria, just south of Topolobampo), near south entrance (not included in final count because this bay was revisited on northern flight and more were counted), 25° N.	(4)	(2)
5 Feb.:	Bahía de la Reforma, on return flight, near south entrance	5	2
	Bahía de la Reforma, near north entrance in channel	13	10
		26	18

In the north channel of Bahía de la Reforma another pair was listed as doubtful. And just north of Bahía Banderas, far to the south between San Blas and Puer-

California gray whale "spy-hopping."
(U. S. Fish & Wildlife Service)

to Vallarta, near 20° N., we saw another whale which might have been a gray, making a possible 47. We flew too fast to have scored the same whale twice, but on the other hand we may have missed some submerged.

The flight covered the Gulf coast from Punta Diggs near San Felipe to Bahía de Los Angeles in the northwest Gulf; thence across the Gulf past the southern end of Isla Angel de la Guarda and Isla Tiburon, to Bahía Kino (landing in the open water near the village), and to Guaymas. The next day we flew to Mazatlán, with stops at the estuary of Río Yaqui, at Estero de la Luna at Punta Lobos, Bahía Huivuilay (Pabellon Colorado), at Puerto Yavaros, at Laguna de Agiobampo (Bucarehius), and Topolobampo. The flight from there, after refueling, was straight to Mazatlán, with orbits over Laguna or Bahía de Navachiste and Bahía de la Reforma (or Santa Maria).

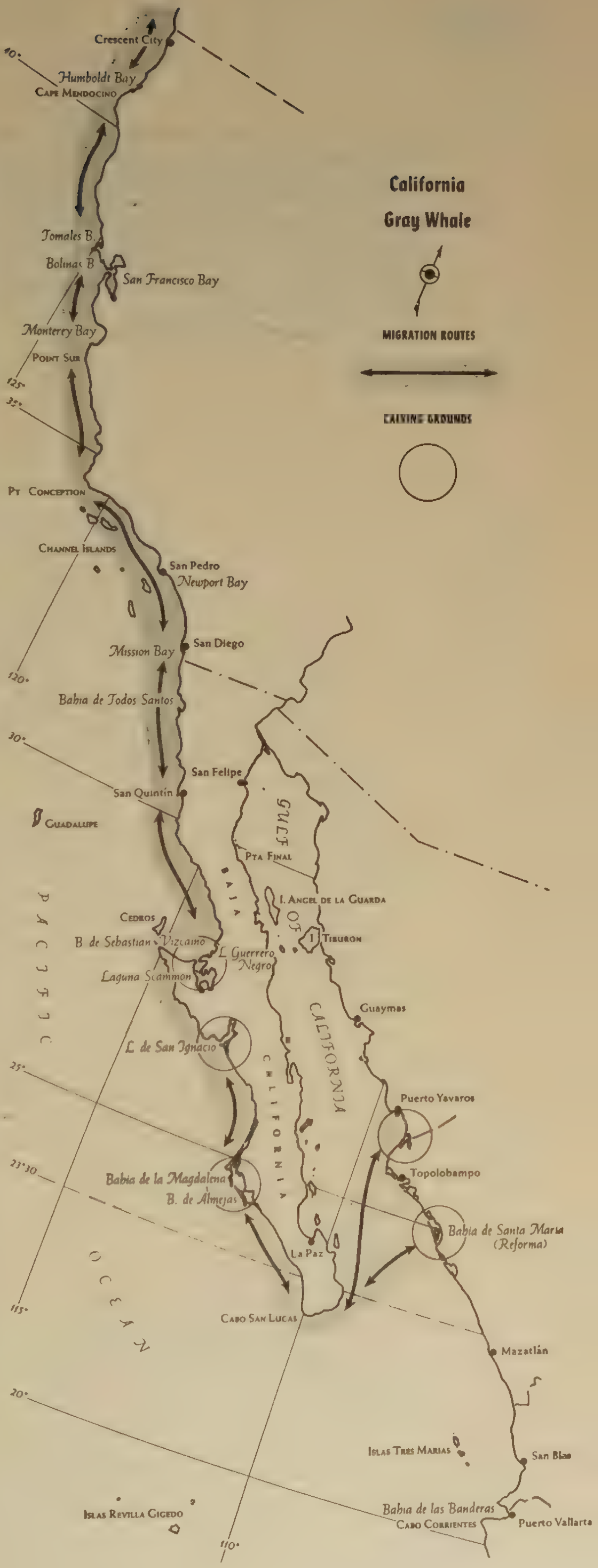
From Mazatlán we made a "round robin" flight to Puerto Vallarta and return, with intermediate stops at San Blas and Isla Santa Isabella to inquire for whales. Coming north from Mazatlán again, before crossing the Gulf to La Paz, we scrutinized Bahía de la Reforma thoroughly along its inside channel near the north and south entrances and outside the island-bar. We saw many more gray whales than on our way south, leading us to replace the count of 3 February with that of 5 February.

Nowhere we stopped and inquired did we learn of whales concentrating in winter in the lagoons or adjacent waters outside, though humpbacks were found common at Isla Isabella just off San Blas, where they were seen apparently mating and feeding.

On a flight over the same area with Ewing on 17-18 February in a Cessna 180, Dr. Hubbs and Mrs. Laura C. Hubbs saw almost the identical number of gray whales in exactly the same places as on the flight by Ewing and Gilmore. This points to well-established residence of the same cows in the same area for the duration of the calving season.

The significance of this discovery of calving grounds on the eastern side of the Gulf of California is that it explains survival of the gray whale during the critical years of heavy whaling from 1850 to 1880 and again from 1924 to 1938, when numbers appeared to have dropped to the vanishing point. Also, the calving grounds on the Gulf are large enough to allow significant increase of the population beyond what issues from the already well known calving lagoons of the west side of Baja California.

Two other facts of interest stand out in thinking about the gray whales in the Gulf; first, the numbers were small, and may never have been large, else the whalers should have discovered them long ago; second, most were cows with calves, indicating that mating takes place chiefly on the west coast of Baja California where intense mating activity has often been observed.



Map prepared for *Pacific Discovery* from data supplied by the authors.

California Gray Whale
MIGRATION ROUTES
CALVING GROUNDS
Crescent City
Humboldt Bay
Cape Mendocino
40°
Tomales B.
Bolinas B
San Francisco Bay
Monterey Bay
Point Sur
125°
35°
Pt Conception
Channel Islands
San Pedro
Newport Bay
Mission Bay
San Diego
120°
Bahia de Todos Santos
30°
San Felipe
San Quintin
Guadalupe
Pta Final
GULF OF CALIFORNIA
BAJA CALIFORNIA
PACIFIC OCEAN
I. Angel de la Guarda
Tiburon
Cedros
B. de Sebastian Vizcaino
L. Guerrero Negro
Laguna Scammon
Guaymas
L. de San Ignacio
25°
Puerto Yavaros
Topolobampo
23°30
Bahia de la Magdalena
B. de Almejas
Bahia de Santa Maria (Reforma)
La Paz
115°
Cabo San Lucas
Mazatlán
20°
Islas Tres Marias
San Blas
Islas Revilla Gigedo
Bahia de las Banderas
Cabo Corrientes
Puerto Vallarta
110°

So far we have not seen whales crossing the open Gulf between Cape San Lucas and the mainland. Possibly some gray whales spend the summer near the head of the Gulf as many finbacks do, and as some grays do at Crescent City, northern California. The lone one seen at Punta Final encourages this idea which, however, is not yet confirmed as fact — except for that one, all the whales seen so far near the head of the Gulf have been finbacks.

Thus, a new chapter has been added to the natural history of the gray whale. Many details of their life cycle remain to be uncovered, some by future flights to Mexico and some from such easy points of observation as the public whale watch maintained by the National Park Service at the Cabrillo National Monument on Point Loma, San Diego. As the full story unfolds we shall learn whether in the future a limited harvest of surplus whales may be permitted for meat and other useful products, without again decimating the population.

Contribution from the Scripps Institution of Oceanography, new series, No. 697.

Adjustment of Bikini Atoll to Ocean Waves

By WALTER H. MUNK *and* MARSTON C. SARGENT

Bikini and Nearby Atolls, Marshall Islands

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-C

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CONTENTS

	Page
Abstract	275
Grooves and surge channels	275
Distribution of grooves and prevailing wave directions	276
Ecological significance of wave action	277
Head of water at reef edge	278
Wave-driven currents over the reef	278
Discussion and conclusions	279
Acknowledgment	279
Appendix 1.—Depth of wave action	279
Appendix 2.—Dimensions of surge channels	279
Appendix 3.—Wave power	280
Literature cited	280

ILLUSTRATIONS

FIGURE 91. Reef grooves and wave power—Bikini Atoll 275
92. Seaward face and top of reef—Bikini Atoll 276
93. Breaking waves in surge channel 280

TABLES

TABLE 1. Mean orbital speed 279
2. Length of channels 279

ADJUSTMENT OF BIKINI ATOLL TO OCEAN WAVES

By Walter H. Munk and Marston C. Sargent

ABSTRACT

Atolls in the trade-wind belt withstand a continuous heavy pounding from ocean waves. Against the windward side of Bikini Atoll alone it is estimated that waves dissipate 500,000 horsepower, one-fourth the power generated at Hoover (Boulder) Dam. To withstand these forces, the exposed reefs are molded into a most effective natural breakwater, consisting of long narrow grooves in the seaward face of the reef, and surge channels on the reef flat. These surge channels are tuned to the prevailing wave periods. Their distribution around the reef conforms to the distribution in wave activity, which in turn is controlled by prevailing winds over the north and south equatorial Pacific.

Some of the power of the breaking waves is utilized to maintain a water level just inside the surf zone about 1.5 feet above the general sea level. The water flows downhill over the reef into the lagoon, regardless of the stage of the tide, with an average speed of 0.5 to 1.0 knot, but occasionally with speeds up to 4 knots. The reef as a biological community utilizes this current and maintains thereby a wave-resisting and modifying structure.

GROOVES AND SURGE CHANNELS

The features to be described here are best developed between Bikini and Aomoen islands (fig. 91), where the reef is directly exposed to the waves of the prevailing trade winds (Tracey, Ladd, and Hoffmeister, 1948). Grooves cut the seaward face of the reef at fairly regular intervals (fig. 92) and give it the appearance of a series of spurs rising from the debris-covered slope of the atoll.

Most of the grooves commence at a depth of 35 to 50 feet, then run up the reef slope into and through the surf zone. At the inner end they may end abruptly or be continued as surge channels, or as tunnels with blowholes under the reef platform. Just inside the

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Note.—Contribution from the Scripps Institution of Oceanography, New Series, No. 698.

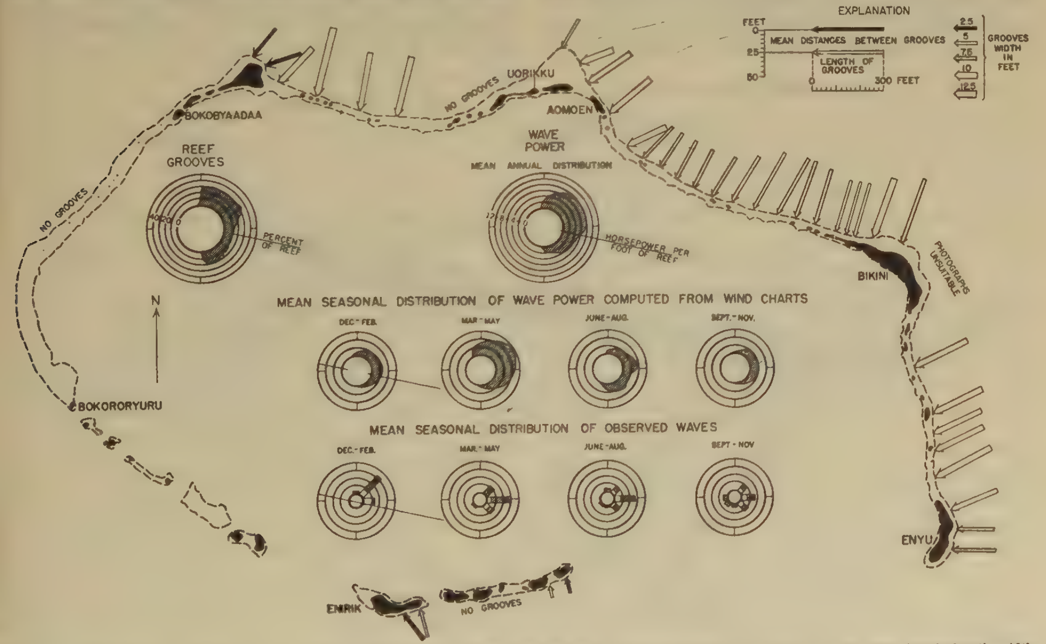
EXPLANATION
FEET
0
25
50
MEAN DISTANCES BETWEEN GROOVES
LENGTH OF GROOVES
0
300 FEET
2.5
5
7.5
10
12.5
GROOVES WIDTH IN FEET
UORIKKU
NO GROOVES
AOMOEN
BOKOBYAADAA
REEF GROOVES
PERCENT OF REEF
WAVE POWER
MEAN ANNUAL DISTRIBUTION
HORSEPOWER PER FOOT OF REEF
NO GROOVES
BIKINI
PHOTOGRAPHS UNSUITABLE
N
MEAN SEASONAL DISTRIBUTION OF WAVE POWER COMPUTED FROM WIND CHARTS
DEC.-FEB.
MAR.-MAY
JUNE-AUG.
SEPT.-NOV.
MEAN SEASONAL DISTRIBUTION OF OBSERVED WAVES
DEC.-FEB.
MAR.-MAY
JUNE-AUG.
SEPT.-NOV.
BOKORORYURU
ENYU
ENIRIK
NO GROOVES

Figure 91.—Distribution of reef grooves and wave power around the reef of Bikini Atoll; the length, width, and spacing of the grooves are proportional to the length, width, and spacing of the arrows drawn against the reef; polar-coordinate graph to the left shows percent of area occupied by grooves as a function of their exposure; polar-coordinate graphs to the right show mean distribution of computed wave power and of observed waves.

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surf zone, around the blowholes and the heads of grooves and channels, colonies of *Lithothamnion* and corals rise about 2 feet above the general reef level. The upper faces of the spurs are paved with living *Lithothamnion* which present an extremely rough surface. The sides of the grooves are covered with projecting, often bracketlike colonies. The bottoms of the grooves consist of relatively smooth rock and sand.

Between Bikini and Aomoen islands the grooves are spaced about 25 feet apart, are about 16 feet deep at their inner ends, and vary in width from 3 to 6 feet. The grooves play a vital part in the function of the coral reef as a breakwater. Near their outer ends, which extend to the maximum depth of appreciable wave action (see appendix 1), they interfere with the normal orbital water motion associated with waves on a sloping bottom by "taking the bottom out from under the waves"; at the inner end they pursue a "divide and conquer" policy. The resulting effect on waves is remarkable. To an observer standing on the platform just inside the surf zone, the breakers at first appear to come crashing down upon him; 2 seconds later the wave has virtually disappeared, its momentum converted into a noisy surge which rushes up the channels on each side of the platform. Much of the remaining energy is spent when the surge meets the backrush from the preceding breaker. Wave energy is also dissipated by friction along the sides of the grooves and channels, where an abundant bracketlike growth of organisms is found.

The surge channels are properly tuned to the average wave characteristics (fig. 92). An average depth of 15 to 20 feet and a length of about 200 feet (*li*, in fig. 92) between the outer end of the platform (*Lithothamnion* ridge) and the inner ends of the channels correspond to a fundamental period of oscillation of 8 seconds, which is also the prevailing period of the waves of the trade winds (see appendix 2). As a result, the uprush of each wave will meet the backrush of the preceding wave at approximately midchannel.

DISTRIBUTION OF GROOVES AND PREVAILING WAVE DIRECTIONS

The dimensions of grooves around the entire reef of Bikini Atoll were estimated from aerial photographs, and are designated by arrows on figure 91. The spacing *s*, width *w*, and outer length *lo* (fig. 92) of the grooves are designated by the spacing, width, and length of the arrows. Photographs of the reef to the south of Bikini island were unsuitable for the determination of the grooves, but it is known that grooves are well developed in that area.

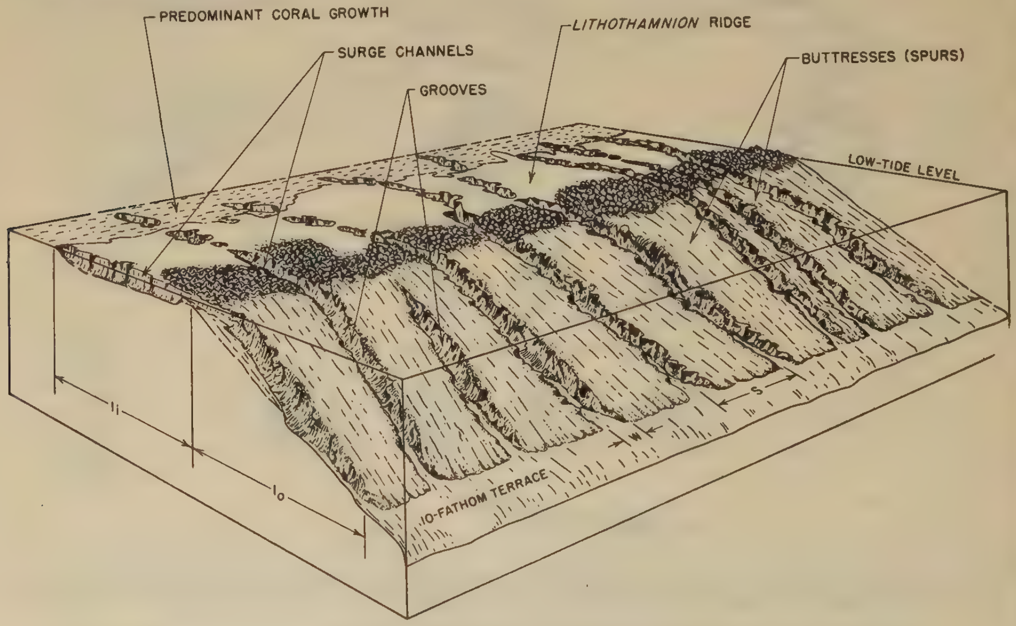

FIGURE 92.—Generalized sketch of seaward face and top of reef on windward side of Bikini Atoll. Original by D. B. Sayner.

The greater length of the grooves with northern exposure relative to those with southern exposure is due to the steeper slope of the reef to the south (Tracey, Ladd, and Hoffmeister, 1948). The absolute depth at which the grooves commence appears to be approximately constant and to extend to the greatest depth for which wave action is appreciable (see appendix 1).

The percent of reef area occupied by the grooves equals $100w/s$. This is plotted as a function of the azimuth of the grooves on the polar coordinate graph on the left in figure 91. No grooves were found where the reef exposure has a westerly component.

The distribution of grooves can be correlated with the distribution of wave power around the atoll. The polar-coordinate graphs to the right in figure 91 give the average seasonal and annual distribution of wave power plotted against reef exposure and expressed in units of horsepower per foot length of reef.

Wave power was computed as follows: The principal generating areas were determined from the "Atlas of climatic charts of the oceans" (U. S. Weather Bureau, 1938); they lie in the trade-wind belts of the north and south Pacific. Swell from the "roaring forties" occasionally reaches the northern Marshall Islands but will be too low to be significant. The frequencies of the prevailing winds in the two main generating areas, and of winds from other directions, were determined from wind roses on the "North and South Pacific pilot charts." The height, period, and direction of waves reaching Bikini Atoll from all directions were then computed, following the method for forecasting sea and swell from weather maps (Sverdrup and Munk, 1946a). Finally the bending of waves around the atoll because of refraction was estimated (Sverdrup and Munk, 1946b) and the wave power computed (see appendix 3).

A rough check of the validity of these computations could be obtained from sea and swell observations appearing in the "Sea and swell charts, northwestern Pacific" (Hydrographic Office 10712C). Averages were formed for each season, taking into account all observations in the area between longitudes 160° and 170° E., and between latitudes 5° and 15° N. These are presented by the wave roses in figure 91. The main features in the observed wave distribution are in agreement with the computed distribution of wave power.

The graph of the annual distribution of wave power is based entirely upon the computed rather than the observed wave characteristics, partly because of the small number of observations but chiefly because the quality of these observations probably is inferior to the quality of the computed values.

The diagrams in figure 91 show a significant correlation between the directional distribution of wave power and reef grooves. Grooves are restricted to reefs with a component of exposure to the east, the direction from which wave action is pronounced. Owing to wave refraction a small portion of the wave power does reach the western sides of the atoll, but there the power dissipated amounts to only a fractional horsepower per foot length of reef, and it appears that at least 1 or 2 horsepower is required for the development of grooves. On the eastern half of the reef the average power delivered by the waves equals 3 horsepower per foot length of reef, or about 20 horsepower per groove.

The distribution of grooves reveals a maximum for an east-northeast exposure, and a secondary maximum for a southeast exposure. These features are associated with the principal wave-generating areas in the trade-wind belts of the north Pacific and south Pacific, respectively. The distribution of wave power reveals the same features; except during the summer months the effect of the distant south Pacific trade winds is overshadowed by the effect of the local trade winds. For a corresponding location in southern latitudes the reverse should be true, and the distribution should be a mirror image of the one found at Bikini Atoll.

The bimodal distribution of grooves points toward a wave origin; if the channels were to be attributed to direct wind action, the development in the southeast quarter would be missing.

ECOLOGICAL SIGNIFICANCE OF WAVE ACTION

The mechanisms by which wave action governs the growth and distribution of reef-building organisms in such a way as to mold the reef cannot be clarified in any detail by data in our possession. It is clear in general that the reef form represents some kind of equilibrium between the erosive or destructive power of the waves and the growth potential of the reef-building organisms. It is generally apparent that in areas where the wave action and hence presumably destructive power is greatest, growth of reef builders is also most rapid (Yonge, 1940, p. 355, 374). Hence windward reef faces may be nearly in equilibrium under conditions of rapid growth and erosion, leeward ones under slow growth and erosion.

The mechanism by which waves promote growth has not usually been distinguished from that of currents. Water motion induced by the waves has been considered to supply nutrients in a broad sense, including gases, mineral nutrients, and sometimes particulate organic matter to the reef organisms. Its importance in removing excreta should also be recognized. That these items can be supplied, or removed, as well by currents as by waves has not usually been mentioned, probably because most previous work has been done on fringing and barrier reefs where transreef currents are small. At Bikini Atoll the current across both windward and leeward reefs is of the order of one knot (30 to 80 centimeters per second), and the mass transport of water through a vertical square centimeter is about a liter every 20 seconds. In the presence of such an abundant supply of nutrient-bearing water (in the widest sense), some other explanation must be sought for the paramount importance of wave action.

In view of the fact that colonies of *Lithothamnion* grow mainly on the wave-beaten edge of the reefs although the waters over the whole reef show no impoverishment of nutrients, it is suggested that the scrubbing action of violently breaking waves is critical. Such action might prevent the settling of particulate matter and the establishment of sessile organisms which could interfere with the nutrient supply and the waste excretion of the reef builders. The erosive action of high-velocity currents has been estimated by Hjulstrom (see appendix 1). It is also possible that the rapid turbulent motion in breaking waves is effective because it rapidly renews the film of water in immediate contact with the surface of the reef-building organisms. Under these conditions molecular diffusion to and from the organism would be entirely eliminated as a possible bottleneck. This suggestion is in accordance with the fact that in the cultivation of small organisms various degrees of stirring are often important. In surf the momentary high velocities in all directions may be effective in stimulating the growth of reef builders—and of the attached surf zone organisms of other localities—even though the net velocity or transport of water and its contents across the reef over a long period of time is practically zero.

The reasons for the changes in frequency and width of grooves and spurs with azimuth are not clear to us. The existence of grooves and spurs strongly suggests a cellular circulation in the water, whether caused and maintained by factors independent of the existence of grooves or spurs or maintained by these features however originated. Tracey, Ladd, and Hoffmeister (1948, p. 873) reasonably propose that the grooves are kept open by a riverlike flow of debris from the reef above and from adjacent spurs and point to the fact that on any vertical plane parallel to the surf zone the orbital velocity of water motion is higher on the spurs than in the grooves. This is a kind of cellular circulation, but it does not for us throw light on the relation between azimuth and groove frequency and width evident in figure 91.

HEAD OF WATER AT REEF EDGE

Not all the energy of the incoming waves is dissipated by friction. Some energy is converted into potential energy to maintain a water level at the outer edge of the reef at about two feet above the mean water level of the ocean and lagoon water. If the entire wave energy were to be consumed in lifting the water which flows over the reef, the level of this volume of water could be maintained 42 feet above the mean sea level (see appendix 3). Therefore only about 5 percent of the wave's energy is utilized to raise the water level, and 95 percent is dissipated by friction, a large part of it within the surge channels.

In designing artificial breakwaters it may be worth while to consider the lines of a coral reef. These natural breakwaters over a period of thousands of years have evolved into structures admirably suited to withstand the wave forces. Artificial surge channels have in fact been employed on the south coast of the Mediterranean in the generation of electricity by means of wave power. These channels were relatively wide at their outer end and converged gradually toward the inner end. In this manner the water level in a reservoir was maintained at an average elevation of 40 feet above the mean sea level.

WAVE-DRIVEN CURRENTS OVER THE REEF

From the region of maximum elevation the current flows into the lagoon under the influence of gravity assisted by wind traction. Between Bikini and Aomoen islands, the speed is about 1 foot per second, except during spring low tides, when the retarding effect of bottom friction is disproportionally large, this speed is remarkably independent of tide. In the presence of obstructions the wave-driven current may give rise to striking features. For example, a few days after the arrival of the U. S. S. *Bowditch* a 100-foot channel broke through the sandspit at the northwest end of Bikini island, and water flowed through this channel in a steady stream for almost 6 months.

Currents over the reef were measured by dropping dye bombs from planes and taking timed photographs of the drifting color patches (Von Arx, 1948). Between February and April 1946, while the trade winds blew predominantly from the east-northeast, wave-driven currents flowed into the lagoon over the entire eastern and northern reefs, adding 3×10^{14} cubic centimeters of water, 1 percent of the entire lagoon volume, during each 12-hour interval. During an equal time interval the tidal flow—chiefly through the deep southwesterly passages—amounted to 2 percent of the lagoon volume. Although the oscillating tidal current represented the principal component of water exchange between the ocean and the lagoon, the one-directional wave-driven current is of primary importance to the renewal of water in the lagoon. This renewal was of interest with regard to the flushing of radio-active water out of the lagoon.

The wave-driven current is important also for another reason. At noon, especially during low tide, the water over the reef becomes warmer, more saline, and supersaturated with oxygen. Upon entering the lagoon, this "reef water" may be recognized as a distinct water type. The mixing of this water with the lagoon water provided a method for computing the rate of vertical diffusion (Munk, Ewing, and Revelle, 1949).

DISCUSSION AND CONCLUSIONS

Waves breaking over coral reefs may lead to the formation of grooves and the flow of currents over the reef. The only other known examples of currents due to wave action are longshore currents and rip currents caused by waves breaking on gently sloping beaches (Munk and Traylor, 1947). Since the waves represent an integrated effect of the winds, their energy being accumulated during many hours, and over thousands of miles, a wave-driven current assures a steadier supply of water than a current maintained by local winds.

The waves and the wave-driven current may be of biological significance in three ways. First, they permit luxuriant growth of *Lithothamnion* and other encrusting coralline algae in situations exposed to the heaviest wave action. Second, the current maintains a nearly constant supply of mineral nutrients and dissolved gases over the whole width of the reef (Sargent and Austin, 1949). Third, as noted above, the current, which at noon is supersaturated with oxygen, carries water into the lagoon.

ACKNOWLEDGMENT

This work represents results of research carried out for the Hydrographic Office, the Office of Naval Research, and the Bureau of Ships of the Navy Department under contract with the University of California. The original of figure 92 was drawn by D. B. Sayner.

APPENDIX 1.—DEPTH OF WAVE ACTION

The average speed of water movement along the bottom in water of depth h is given by

$$u=2\pi\frac{H}{T}\sinh^{-1}\left(\frac{2\pi h}{L}\right) \qquad (1)$$

where H and T are the height and period of the wave responsible for the water movement. The wave length is given by

$$L=\frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \qquad (2)$$

where g is the acceleration due to gravity. For a wind speed of 16 knots, blowing over a long fetch and for a long time, the wave height and period equal 7 feet and 8 seconds, respectively (Sverdrup and Munk, 1946a). These figures are in agreement with the observed dimensions of trade-wind waves. Simultaneous solution of (1) and (2) leads to the numerical values shown in table 1. The outer ends of the grooves fall into a depth of about 50 feet, where the average speed due to wave action is about 1.2 feet per second. The third column shows the size of particles which can be eroded by a current of speed u, based upon measurements in rivers by Hjulstrom (Trask, 1939, pp. 10–11). According to Hjulstrom, ". . . fine sand, which has a diameter of 0.3 to 0.6 mm, is the easiest to erode, whereas both silt and clay on the one hand and coarse sand and gravel on the other require higher velocities." If these conclusions are applicable here, they indicate that no erosion can take place for current speeds less than 0.5 feet per second—that is, at depths exceeding 100 feet, no matter how small the size of the grains.

TABLE 1.—*Mean orbital speed on the ocean bottom*

Depth h (feet)	Speed u (ft/sec)	Size of particles which can be eroded (mm)
50	1.2	3
75	.8	1
100	.5	.05
125	.3	(1)

[1] No erosion.

At a depth of 50 to 75 feet the reef slope is relatively gentle, forming virtually a terrace (Tracey, Ladd, and Hoffmeister, 1948). One would be tempted to ascribe this "10-fathom terrace" to wave action were it not for the fact that it is also found inside the lagoon.

APPENDIX 2.—DIMENSIONS OF SURGE CHANNELS

The speed of a surge in a channel equals approximately $\sqrt{gh}$, where h is the depth of the water measured from the highest point in the surge. For effective interference the surge must travel a distance of roughly the length of the channel during one wave period (fig. 93). The corresponding length of the channel equals approximately $T\sqrt{gh}$. Setting $g=32.2$ feet per second and $h=15$ feet, leads to the values shown in table 2.

TABLE 2.—*Length of channels for maximum interference*

Period T (seconds)	Length (feet)
6	130
8	175
10	220

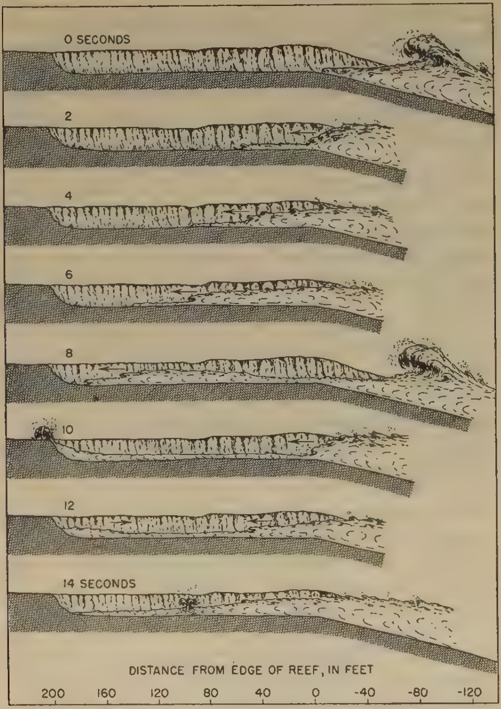

FIGURE 93.—Breaking wave produces surge which travels up the surge channels, is reflected on the upper end, and meets surge from subsequent breaker midchannel; surge channels are tuned to the period of prevailing waves.

The wave period in the region of the northern Marshalls is remarkably constant and falls within the limits of 7 to 9 seconds, probably more than 90 percent of the time. Over most ocean areas the period of the significant waves varies between such wide limits (probably 6 to 14 seconds) that resonance for any permanent structure would be achieved only a small fraction of the time.

APPENDIX 3.—WAVE POWER

The mean energy dissipated by the waves each second against a unit width of reef is $(1/32\pi)\rho g^2H^2T$ where ρ is the density of water. The transport of water per foot width of reef equals $h'V$ where h' is the depth of water over the reef, V the corresponding speed of flow. If the entire wave energy were to be utilized in raising the water flowing over the reef, then

$$\frac{1}{32\pi}\rho g^2H^2T=\rho gh'Vs, \qquad (3)$$

so that the vertical distance through which the water would be raised is

$$s=\frac{g}{32\pi}\frac{H^2T}{h'V}.$$

Setting $H=7$ feet, $T=8$ seconds, $h'=3$ feet, and $V=1$ foot/second gives $s=42$ feet.

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SUBMARINE GEOLOGY OF SAN PEDRO SHELF

BY

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 24, NO. 3, PP. 162–181
PLATES I–V, FIGS. 1–8, SEPTEMBER, 1954

SUBMARINE GEOLOGY OF SAN PEDRO SHELF[1]

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ABSTRACT

The submarine area off San Pedro, California, consists of a shallow shelf which extends seaward 3 to 12 miles and is bordered by a steep escarpment leading down into the deep San Pedro Basin. The shelf and escarpment are cut by a prominent sea valley and two smaller valley-like features.

Shale, limestone, and sandstone of middle Miocene age are exposed on the central shelf. Late Miocene mudstone crops out on the shallow inner shelf, and early Pliocene siltstone occurs on the steep escarpment at relatively great depths. The ages and distribution of the rocks indicate that the lithology and structure of nearby Palos Verdes Hills extends southeastward onto the submarine shelf and escarpment.

Unconsolidated sediments on the shelf are subdivided into six types according to their texture and color. Finest sediment is found behind the breakwater inclosing the shoreward part of the area. Coarsest sediment is a yellowish brown sand on the central shelf and is believed to be residual from Pleistocene conditions. Sediment sorting within the area correlates well with known currents.

INTRODUCTION

San Pedro Shelf is a relatively shallow submarine area which extends a maximum of 12 miles southward from the city of Long Beach to the 40 fathom break in slope (fig. 1). The eastern boundary is arbitrarily defined as the meridian of 118° 03′ West longitude. Approximately one-fifth of the total San Pedro Shelf is within the Federal breakwater. The breakwater incloses the northern part of San Pedro Bay, except for a small sector on the east and forms the Los Angeles-Long Beach Outer Harbor.

Emery and Shepard (1945) have described rocks from five localities off San Pedro and the area was included in a discussion of the sediments off the California coast by Revelle and Shepard (1939). In addition, considerable sampling and test hole drilling have been conducted in the harbor area in connection with engineering projects. The results of a number of test holes drilled in Long Beach Harbor are described by Evans (1949). Dredging operations by the United States Army Corps of Engineers have also furnished useful information (H. W. McOwat, personal communication).

The writer wishes to thank Dr. K. O. Emery of the University of Southern California for his supervision and guidance and Mr. Robert W. Crouch, who kindly identified the Foraminifera in many of the rocks and sediment samples. Appreciation is also expressed to the Allan Hancock Foundation for the use of their sampling equipment and for the opportunity to collect several large dredge samples from the research ship *Velero IV*. The investigation was made possible through the interest and backing of the State of California Department of Public Works, Division of Water Resources.

GEOLOGY OF THE ADJACENT COAST

Physiography

The coast bordering the San Pedro Shelf may be divided into two distinct units. These are the northwest-southeast trending structural highland of Palos Verdes Hills, (sometimes called San Pedro Hills), west of San Pedro, and the coastal plain to the north and northwest.

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[1] Contribution of Allan Hancock Foundation No. 140. Contribution of Scripps Institution of Oceanography, new series No. 699.

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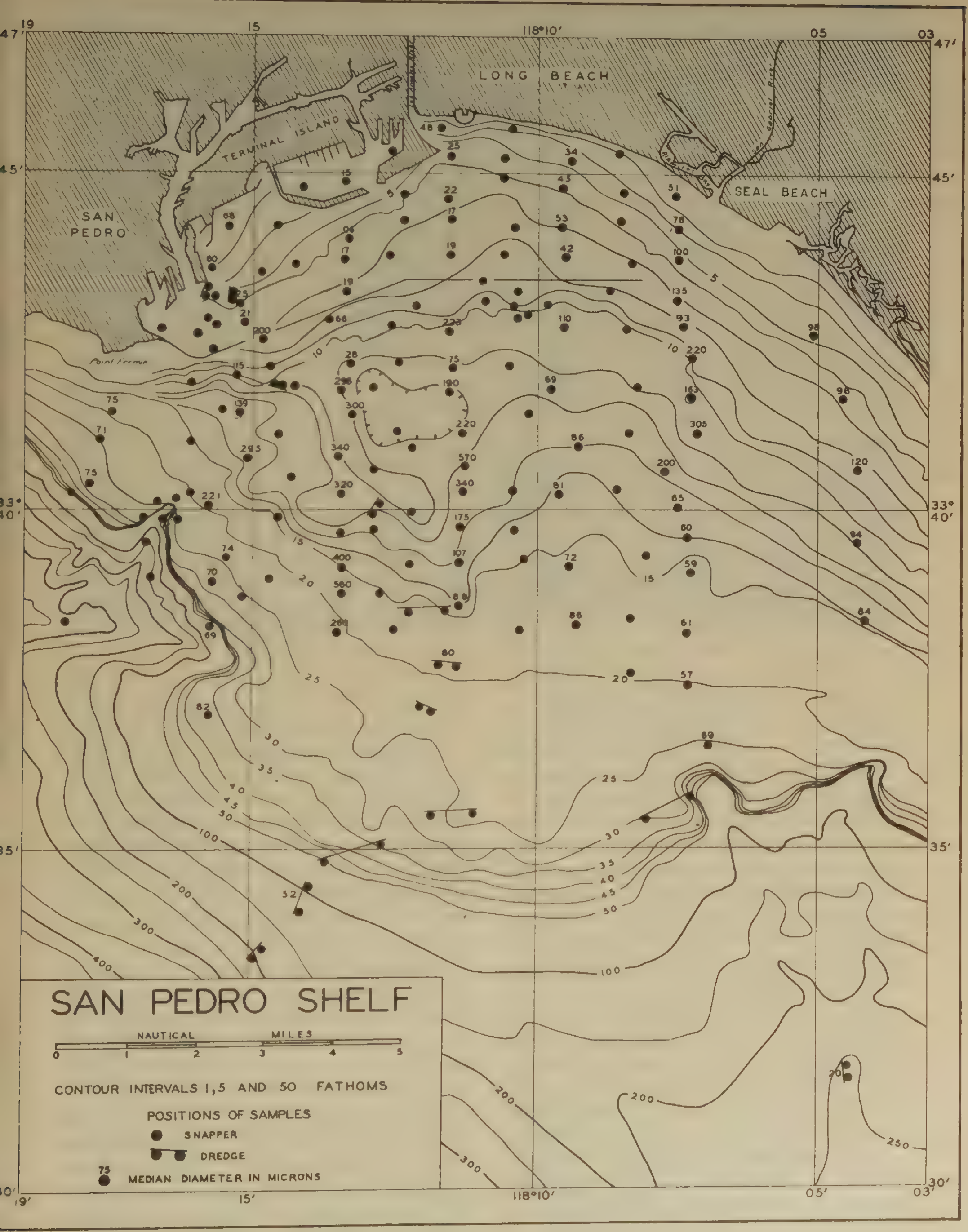
SAN PEDRO SHELF
NAUTICAL MILES
0
1
2
3
4
5
CONTOUR INTERVALS 1, 5 AND 50 FATHOMS
POSITIONS OF SAMPLES
● SNAPPER
DREDGE
75
● MEDIAN DIAMETER IN MICRONS
LONG BEACH
TERMINAL ISLAND
SAN PEDRO
SEAL BEACH
Point Fermin
19
15
118°10′
05
03
47′
45′
33° 40′
35′
30′
19′
15′
118°10′
05′
03′
5
10
15
20
25
30
35
40
45
50
100
200
250
300
400

FIG. 1.—Topography and sample positions.

Palos Verdes Hills are the dominating physiographic feature of the area with a maximum elevation of 1480 feet. The upper slopes of the hills are characterized by a rolling mature topography, whereas the lower portions are marked by a series of marine terraces which terminate in sea cliffs to the south and west.

In contrast to Palos Verdes Hills, the coastal plain is a low flat surface on which there is a group of small uplifted areas associated with the Newport Inglewood fault zone (fig. 3). Signal Hill, in Long Beach, is most prominent among these. Farther southeast, other gentle rises occur at Seal Beach and Huntington Beach. Between the cliffed shorelines of the uplifted areas are marshlands and bays, all of which are protected by barrier beaches. These and normal beaches fringe the entire shoreline, with the exception of the Los Angeles-Long Beach Harbor.

Stratigraphy

Exposures of basement rock and Tertiary and Quaternary sedimentary rocks occur in the Palos Verdes Hills which are representative of most of the stratigraphic units known to exist beneath the alluvium covered coastal plain. The exposures in Palos Verdes Hills have been described by Woodring, Bramlette and Kew (1946). Basement rocks consist of Jurassic (?) shists and altered basic igneous rocks. Overlying the basement rocks are the middle Miocene Altamira shales, limestones, and sandstones, Upper Miocene Valmonte Diatomite and Malaga Mudstone, and the Lower Pliocene Repetto Siltstone. Pleistocene sands and gravels which underlie the recent fluvial deposits of the coastal plain are exposed on the north and east flanks of Palos Verdes Hills. The Pleistocene deposits have been classified as the Lower Pleistocene Lomita Marl, Timms Point Silt, and San Pedro Sand, and the Upper Pleistocene Palos Verdes Marine Terrace Cover. Recent non-marine material occurs as terrace cover in the Palos Verdes Hills, and as fluvial deposits on the coastal plain.

SUBMARINE TOPOGRAPHY

Information regarding the topography of the San Pedro Shelf area was obtained from soundings on unpublished hydrographic sheets of the United States Coast and Geodetic Survey, from published chart 5142, and from fathograms made aboard the *Velero IV*. Figure 1 shows the area contoured on 1, 5, and 50 fathom intervals.

The sea floor off San Pedro is composed of three topographic units: the shelf; the steep slope forming the southern boundary of the area; and the submarine valleys which indent the slope. Fathograms of the major topographic features are shown in plate I.

The shelf is best developed in the central area due south of Long Beach, where it is 11.5 nautical miles wide. On this widest part the average slope from the shore to 25 fathoms is 8.5 minutes which is very close to the average of 7 minutes for the continental shelves of the world (Shepard, 1948, p. 144). San Pedro Shelf, however, is much narrower and shallower than the average. The only significant topographic irregularities on the shelf occur on the wide central area. A low broad northwest-southeast trending topographic nose extends the 11 fathom contour seaward for about 3½ miles. Beyond this point the nose slopes gently seaward. Northeast of this nose is a roughly circular depression about one mile in diameter and about 1 fathom deep. East and west of the central area the shelf has a smooth surface and is narrower and somewhat steeper.

The steep slope forming the southern boundary of the area has been named the San Pedro Escarpment by Shepard and Emery (1941). At the western edge of San Pedro Shelf, the escarpment has an average slope of 51 minutes between 25 and 50 fathoms, and 7° 25′ from 50 fathoms to the floor of San Pedro Basin. West of the San Pedro Shelf, off Palos Verdes Hills, the escarpment is steeper and relatively straight which led Shepard and Emery to postulate a tectonic origin.

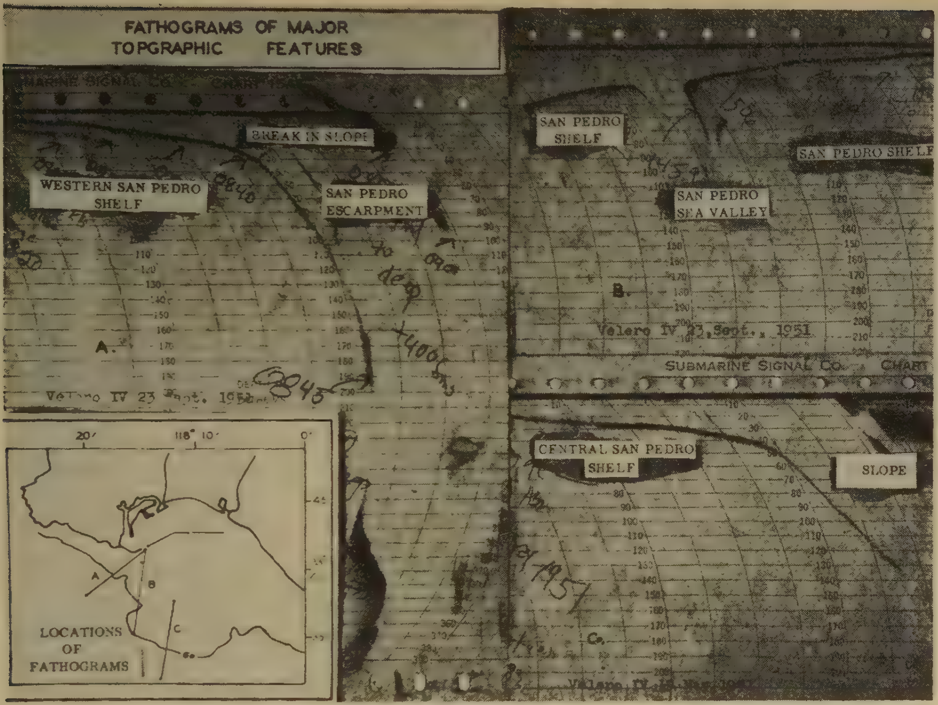

PLATE I.—Fathograms of the major topographic features.

East of the widest part of the San Pedro Shelf, the slope loses the appearance of a fault scarp.

Perhaps the most striking topographic feature of the area is the sharp indentation in the San Pedro Escarpment south of Point Fermin. Shepard and Emery named this feature San Pedro Sea Valley. The general trend of the valley is east-west, but towards its head a branch extends to the northeast towards the mouth of the San Gabriel River ten miles away. No topographic connection between the river and valley are now evident on the shelf.

A smaller sea valley cuts the slope at the eastern margin of the area. The feature appears at about 350 fathoms and extends northward up the slope. At 250 fathoms it divides into twin valleys both of which cut about one mile into the shelf. The twin valleys have grades only slightly steeper than that of the adjacent slope.

CURRENTS

Far offshore, beyond the Channel Islands, a mass southerly transport of water called the California Current flows throughout the year. During all but the spring months, a counter-current operaates, causing a northward flow of surface water. Part of this flow turns inshore and south again, and the resulting southeastward movement of water overlaps the San Pedro Shelf area. In the spring when the surface flow of the countercurrent is prevented by strong northwest winds, the California Current extends to the nearshore area and continues the southeasterly flow of the normal coastal current (Sverdrup and Fleming, 1936–41; Sverdrup, *et al.*, 1941–44, 1947).

Longshore currents are present within

the breaker zone, and for a short distance seaward. Their direction of flow is determined by the configuration of the coastline and the direction of approach of the generating waves (Shepard, 1950). South of Long Beach, longshore currents presently flow predominately to the northwest into the outer harbor, but before the completion of the Long Beach detached breakwater in 1930 the direction of flow was to the southeast, directly the opposite of the present trend. This reversal was caused by the breakwater preventing all but southerly waves from reaching the shore in the area of current generation. Further southeast of Long Beach, the direction of flow of longshore currents still is largely to the southeast, except during periods of strong southerly swell, which causes a reversal in the direction of flow.

BOTTOM SAMPLES

Collection and Treatment

Eleven of the total of 161 samples were collected aboard the *Velero IV* with a heavy rock dredge. The remaining 150 were taken from the boat *Spearfisher*. All but three of the *Spearfisher* samples were taken with a snapper-type bottom sampler, which under ideal conditions obtains about one pint of sediment. The three remaining samples were collected with a small triangle dredge.

Laboratory descriptions of the sediments and rocks were made with hand lens and binocular microscope. A composite of each sediment type was examined in order to determine the approximate composition and such features as surface texture and shape. Colors of all sediments and rocks were classified according to the Munsell color system (Goddard, *et al.*, 1948).

The foraminifera faunas of many of the rock and unconsolidated sediment samples were examined by R. W. Crouch.

Igneous rocks are principally transported pebble-sized fragments of granitic composition. The larger igneous and metamorphic rocks which were essentially in place were identified by thin-section and petrographic microscope. Several of the limestones and sandstones were treated with dilute hydrochloric acid in order to determine the clastic:carbonate ratio.

Mechanical analyses of sediments were made by pipette, settling tube (Emery, 1938), or sieving according to the size distribution of the sample.

Rock Samples

General

From the 25 samples containing rock, a total of 741 individual specimens were examined and described. The positions of the rock samples are plotted on figure 2 along with the outlines of a yellowish brown sand area which bears important relationships to many of the rock samples.

Age determinations of the rock samples were based on foraminiferal content and lithologic comparisons with rock cropping out on the coast. Rock samples from several localities contained nondiagnostic forms or were barren of fossils hence their ages are based entirely on lithologic comparisons.

Criteria for recognizing rock samples from the sea floor as being essentially in place were established by Emery and Shepard (1945, pp. 433–434). Their criteria are: abundant rocks of similar lithology, fresh fractures, fragile or poorly consolidated rock, and general angularity, large size of individual rocks, catching of the dredge on rocks firm enough to stop the ship's progress; and strong pull on the accumulator spring of the dredging boom. Substantial evidence is obtained when several of these criteria apply to a single sample.

Age and Distribution of Rock Types

Rocks essentially in place: Four areas are distinguishable from which rocks believed to be essentially in place were recovered. These are: (1) west end of outer harbor and inner shelf, (2) west central shelf, (3) outer shelf and escarpment, and (4) San Pedro Sea Valley. For conveni-

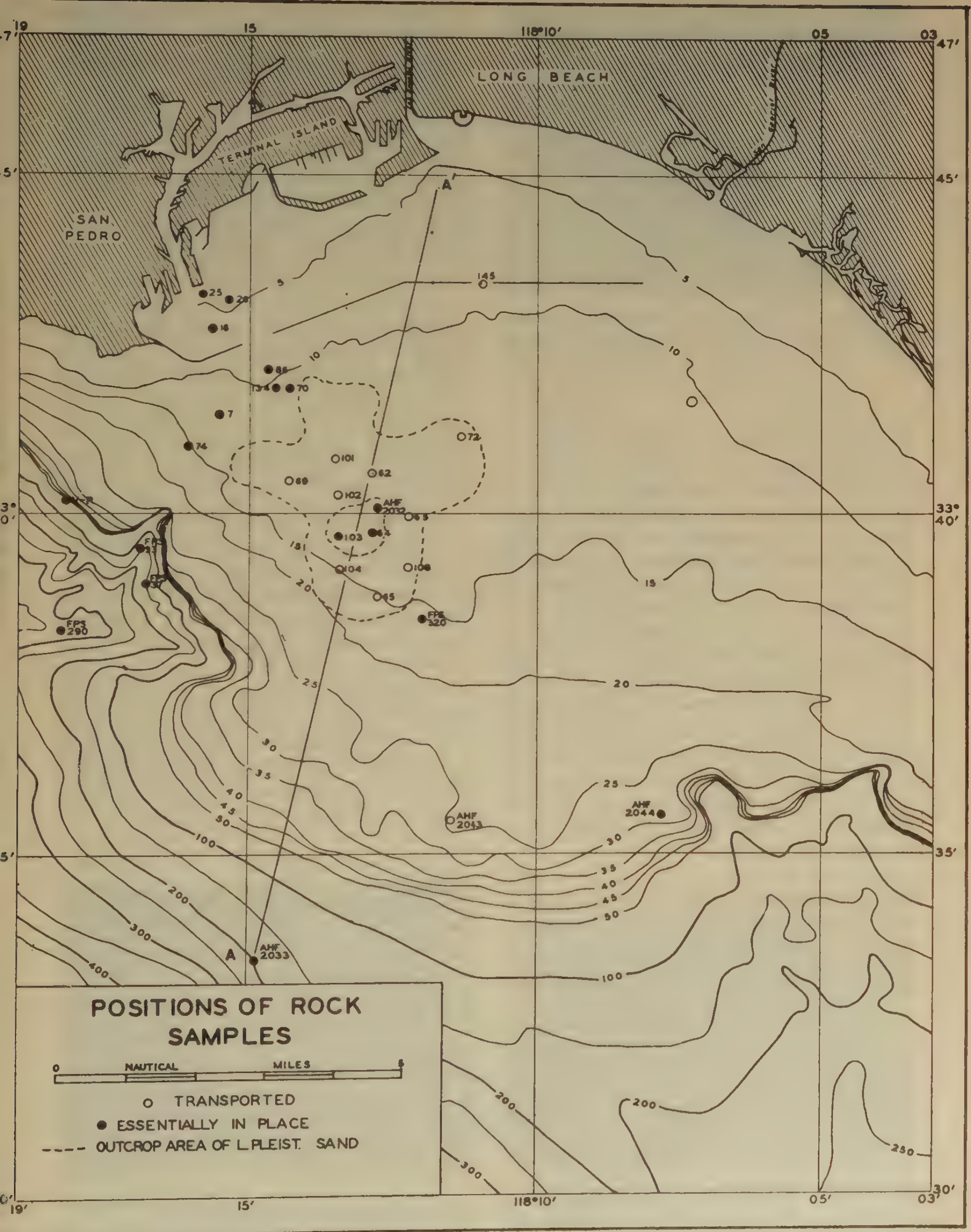
POSITIONS OF ROCK SAMPLES
0 NAUTICAL MILES 5
○ TRANSPORTED
● ESSENTIALLY IN PLACE
---- OUTCROP AREA OF L. PLEIST. SAND
LONG BEACH
TERMINAL ISLAND
SAN PEDRO
A
A'
19
15
118°10'
05
03
47'
45'
33° 40'
35'
30'
19'
15'
05'
03'
145
25
16
86
134
70
7
74
101
69
62
102
AHF 2032
63
103
64
104
106
65
72
FPS 320
FPS 290
AHF 2043
AHF 2044
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Fig. 2.—Positions of rock samples.

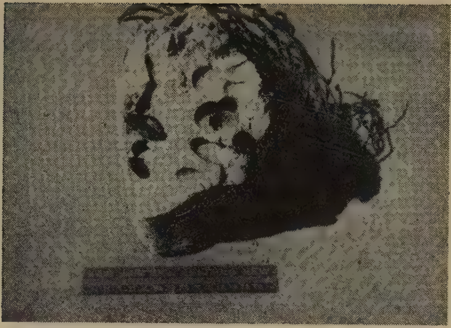


Plate II.—Middle Miocene sandstone from the outer harbor (Sta. M 26). Note the Gorgonid coral and the many pholad borings.

ence, each area is discussed independently.

(1) West end of outer harbor and inner shelf: Rock outcrops in the outer harbor south of Reservation Point are well known to harbor engineers inasmuch as they were formerly a navigational hazard. The shallowest of these outcrops, known as Weldt Rock, was partially removed by blasting. Weldt Rock (figure 2, sta. 26) consists of gray medium-grained sandstone, well cemented with calcium carbonate. The grains are predominantly angular quartz, but a significant amount of feldspar and dark hornblende and biotite is present. Pholad borings are extremely abundant, some containing living pholads (pl. II).

A short distance northwest of Weldt Rock is another outcrop which is composed largely of dark gray, hard porcelaneous shale and white cherty, silty shale. Dark olive gray, fine crystalline limestone and soft massive olive gray mudstone were also recovered. Several hundred feet north of this locality was the now non-existent Deadman's Island. As described by Woodring, Bramlette, and Kew (1936) the island consisted of Pleistocene and Recent sediments overlying the upper Miocene Malaga mudstone. The mudstone dredged south of the site of Deadman's Island represents an extension of this formation beneath the harbor. Lithologic evidence indicates that the hard shale, sandstone, and limestone are part of the middle Miocene Altramira formation, so their outcropping suggests only a thin section of Mallaga mudstone at this location. Small angular fragments of mudstone were also recovered directly south of Weldt Rock.

Still farther south, beyond the breakwater on the western inner shelf, additional samples of soft light olive gray mudstone were recovered. Because the mudstone is friable when wet all occurrences were taken to indicate an outcrop area. As further evidence, two stations yielded rock which was obviously broken from an outcrop. The mudstone shows a typical greasy streak when scratched with the fingernail, and all samples were considerably affected by worm borings (pl. III). Because of the softness of the mudstone, sand grains and microfossils were impregnated in its surface layers which led to some confusion as to its age. In order to obtain more positive proof, a dredge haul was made in the area and large fragments were recovered. These were found to contain a distinct upper Miocene (Delmontian) fauna. On the basis of the faunal determinations from the larger sample, the other lithogically similar pebble-sized mudstone fragments were also classified as upper Miocene Malaga mudstone.

Plate III.—Upper Miocene mudstone from stations M 134 and M 70 on the western part of the inner shelf. Note the angularity of the fragments and the worm borings.

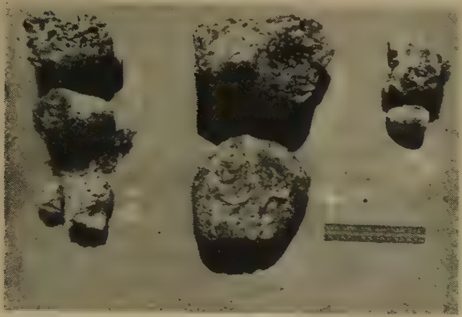


Plate IV.—Middle Miocene rocks from Station AHF 2032 (Horseshoe Kelp): (1) Hard crystalline limestone; (2) Shelly limestone; (3) Porcelaneous laminated shale; (4) Welded tuff; (5) Quartzite. Note the pholad borings.

(2) West central shelf: Abundant rocks essentially in place were found on the west central shelf. These consisted largely of the hard, laminated, porcelaneous, rhythmically banded shale typical of the Monterey formation in the Palos Verdes Hills. More than 90 pieces of this rock were recovered in one dredge haul, and one boulder had a diameter of 51 centimeters. In addition to the shale, sandy, shelly, olive colored limestone was sparsely represented. Two large boulders of welded tuff (ignimbrite) and some fragments of quartz schist similar to that described by Woodford (1924) were present among the shale boulders. Many of the large rocks were sub-round to subangular (pl. IV), indicating that in the past the rocks may have been subjected to wave action. Despite the rounding, the excessive number of rocks of similar lithology and the large size of many of the individual rocks attest to their being near an outcrop. The typical Monterey lithology of the shale was taken as sufficient evidence for assigning a middle Miocene age to the shale. Limestones similar to those dredged along with the shale also occur in the Palos Verdes Hills in the Altamira formation. The age of the welded tuff is not certain but probably can be classified along with the sedimentary rocks as middle Miocene, as pyroclastic material is associated with the Miocene basalts of the Palos Verdes Hills. Quartz schist, like that dredged from the western shelf, has been assigned a possible Jurassic age by Woodford. The fragment recovered was evidently reworked into the Miocene sediments.

A number of fragments of recently formed sandy limestone were also recovered from the west central shelf. The material was composed of yellowish brown medium sand and many living reef-forming organisms cemented with calcium carbonate. The rock was poorly consolidated when wet but became much firmer upon drying. Recent formation of this material was well shown by an embedded bottle.

(3) Outer shelf and escarpment: A dredge haul on the eastern outer shelf recovered a single specimen of dark-gray hard finely crystalline limestone. The rock measures 15 centimeters in maximum diameter and was angular. Many pholad borings are present, but no living pholads were found. Because only one rock was recovered in the dredge haul there is a possibility that it may have been transported to this locality by floating kelp (Emery, 1941). However, notations on the navigational chart, indicate a considerable area of rock bottom at this locality, and it is probable that if further dredge hauls had been possible more rock would have been recovered. The single

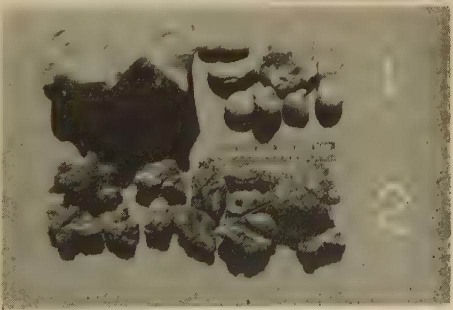


Plate V.—Lower Pliocene rocks from Station AHF 2033: (1) Hard mudstone concretions; (2) Soft siltstone. Note the angularity of the siltstone.

piece of limestone was classified as essentially in place because of its large size and angularity. Lithologically, the limestone is similar to the siliceous limestone in the Altamira formation of Palos Verdes Hills.

On the western escarpment at a depth of 200 fathoms, a large dredge load of massive, angular, olive colored soft siltstone, and hard sandstone and mudstone concretions was obtained (pl. V). Foraminifera in the siltstone were found to be lower Pleistocene (Repetto) in age. The concretions range up to 21 centimeters in diameter and are primarily hard massive calcareous mudstone, shaped in elongate cigar-like figures and irregular round masses. The soft Pliocene siltstone is pierced by numerous borings of about the right size for pholads, which may indicate a former shallower environment. When brought aboard the ship, the rocks were enclosed by a plastic mass of silt and clay, indicating a thin sediment cover over the outcrop. Also present in the same sample were two barite concretions (Revelle and Emery, 1951). The largest of the barite fragments was five centimeters in diameter, and both were roughly tabular in shape. The surface of the barite was rough and had a botrioidal appearance. In contrast to the olive color of the enclosing siltstone, the barite was pale yellow.

(4) San Pedro Sea Valley: Rock has been recovered by previous workers from five localities in the San Pedro Sea Valley. In the eastern extremity of the valley at 100 fathoms depth an area was sampled consisting principally of dark gray crystalline limestone with some sandstone and shelly limestone. Most of the rock is angular to subround and is considered to be at or near a limestone outcrop. About a mile north of the limestone outcrop, an area of angular gray massive siltstone was located. Pliocene foraminifera are reported from this rock, and it is assumed that it is the Repetto siltstone, like that found on the escarpment farther south. A few small angular fragments of mudstone were found in the central valley at a depth of more than 300 fathoms. The mudstone contains only a few nondiagnostic diatoms and therefore could not be correlated with any coastal type. Mudstone was obtained on the northern lip of the sea valley, which was identified as upper Miocene. This outcrop is in line with the southwest trend of the Malaga mudstone exposures on the western inner shelf, and is therefore considered to represent a seaward continuation of the upper Miocene strata.

Transported Rocks: Rock considered to have been transported to the locality of sampling was recovered from three areas on the San Pedro Shelf. These are the: (1) Central inner shelf, (2) West central shelf, and (3) Central outer shelf.

(1) Central inner shelf: One sample at the Long Beach entrance of the breakwater contained several pebbles of soft olive gray mudstone, small chips of limestone and sandstone, and many small pebbles of granitic rock. All of these rocks probably represent material utilized in the construction of the breakwater.

(2) West central shelf: Nine snapper samples taken on the west central shelf, surrounding the area of outcropping middle Miocene rock, yielded 317 pebbles. All of these pebbles are enclosed in yellowish brown sand (figure 2). Seventy per cent of the pebbles are limestone, largely of the brownish yellow, hard, fine crystalline variety. More than half of the limestone pebbles are chips left after pholads had completely riddled a rock, as is shown by their irregular faceted shapes. Most of the remaining pebbles are hard well-cemented sandstones and porcelaneous shales similar to those of the middle Miocene strata of Palos Verdes Hills. A few miscellaneous pebbles of granite, quartz, hard mudstone, and phosphorite were also recovered. Nearly all of the pebbles show some degree of rounding, and many are well rounded.

The significance of these pebbles associated with the yellowish brown sand lies in the fact that pebbles of similar characteristics are found in the Lower Pleistocene Timms Point silt and Lomita marl of Palos Verdes Hills. Woodring, Bramlette, and Kew (1946, pp. 44–45, 53) in describing the Timms Point formation, mention, that at the type locality the yellowish brown silt and sand locally contains pebbles of limestone like that in the underlying Miocene strata. In discussing the Timms Point formation at the now destroyed Deadman's Island, they state that, "The Timms Point silt consisted of massive brownish sandy silt and silty sand locally cemented. At the base were pebbles of limestone and hard mudstone." The occurrence of the pebbles in the Timms Point and Lomita formations, similar to those in the yellowish brown sand on west central San Pedro Shelf, is evidence that the yellowish brown sand and pebbles may be residual from sediments of Lower Pleistocene age.

(3) Central outer shelf: Just shoreward of the break in slope on the central outer shelf, the dredge recovered 77 small granitic pebbles and several chips of hard yellowish brown limestone. Coarse sand was found with the pebbles, and as all of the coarse material was washed free of a mass of fine sand and silt after the dredge was brought aboard the ship, it is believed that a thin veneer of the fine material constituted the surface layer of the bottom. These granitic pebbles may be part of a deposit which was laid down during times of lowered sea level, in Late Pleistocene time. In a report on the geology of the west basin of Los Angeles, California, Richter (1950) shows a seaward projection of the longitudinal profile along the base of the gravels deposited by an Ancestral San Gabriel River. His projection intersects the shelf, in the region of this dredge sample, at the 50 fathom contour. The gravel dredged from the outer shelf may, therefore, represent deposits of the Ancestral San Gabriel River.

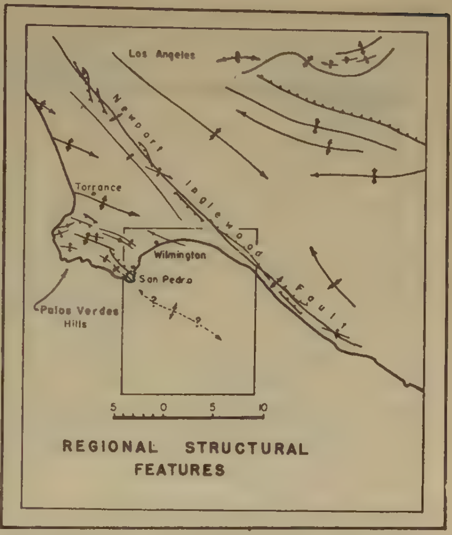


FIG. 3.—Regional structural features.

Structural Implications

On the basis of the ages and locations of rock and sediment types the following large-scale structural features are postulated:

(1) A seaward extension of the structural unit of Palos Verdes Hills is indicated by middle Miocene rocks recovered from the west central and eastern outer shelf. The positions of the rock samples show a southeastward trend for the extension which is in harmony with other regional features such as the Newport-Inglewood fault zone, the Wilmington and Torrance oil field structures, and the major structural features within the Palos Verdes Hills (fig. 3).

(2) An anticlinal nature for the structure extending beneath the San Pedro Shelf is suggested by the recovery of lower Pliocene rock from a depth of 1,200 feet on the escarpment forming the southern limit of the shelf, and middle Miocene rock from a depth of only 60 to 80 feet on the central shelf. Figure 4 is a *hypothetical* cross section across the shelf showing the location of the lower Pliocene outcrop, the middle Miocene outcrop in the relatively shallow water of the west central shelf and the "lower Pleistocene" sand which surrounds the middle

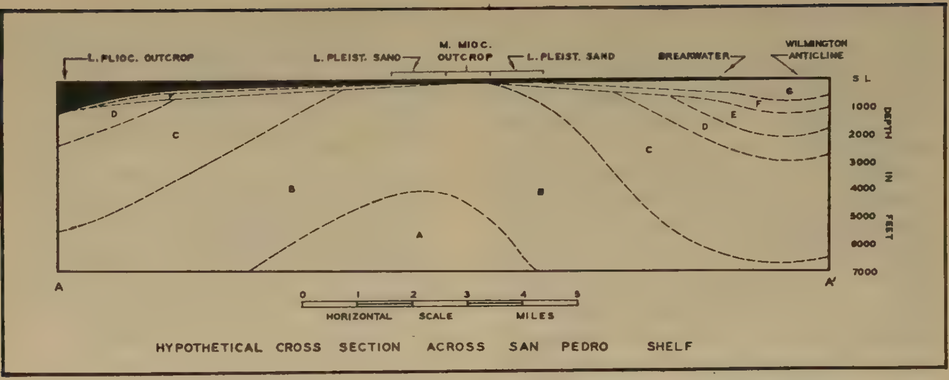


FIG. 4.—Hypothetical cross-section across San Pedro Shelf. G—Upper Pleistocene to Recent; F—Lower Pleistocene; E—Upper Pliocene; D—Lower Pliocene; C—Upper Miocene; B—Middle Miocene; A—Jurassic (?) basement. For location of section see figure 2.

Miocene rocks. The stratigraphy of the south flank of the Wilmington anticline (Winterburn, 1943) was projected southward to explain the occurrences of outcropping rock on the shelf. It should be noted again that the cross section is hypothetical and no direct evidence was found which indicated a continuous stratum of lower Pleistocene sand beneath the shelf, or the existence of the indicated unconformities. The simplified picture shown in figure 4 would unquestionably be complicated by faulting and minor folding.

(3) A structural saddle or a fault evidently separates the middle Miocene rocks of the central shelf from that which crops out on Point Fermin to the northwest. This is shown by fossiliferous upper Miocene mudstone found cropping out between the two areas of middle Miocene lithology.

Unconsolidated Sediments

Classification

Chiefly on the basis of texture and color, the sediments were classified into 6 different types: (1) "black very fine sand to clay," (2) "olive gray very fine sand to clay," (3) "olive gray fine sand to coarse silt," (4) "olive gray very fine sand," (5) "olive gray medium and fine sand," and (6) "yellowish brown coarse to fine sand." The names of the sediment types include only those size grades which make up 10 per cent or more of the sediment.

In order to illustrate graphically the sediment types, the data from mechanical analyses were averaged from all of the samples comprising each of the six types; and an average histogram of each is shown in Figure 5. Aerial distribution of the various sediment types is shown in Figure 6.

Sediment Types

"Black very fine sand to clay": This is the least extensive of the sediment types. Inside the breakwater, the black color is the result of reducing conditions brought about by a sewer which empties organic rich material into the outer harbor on the southwest side of Terminal Island. An odor of hydrogen sulfide is clearly discernible in all the black sediment but is considerably stronger in the north near the sewer outlet. The black color does not extend eastward, but continues southward to the breakwater, suggesting that this section of the outer harbor is not exposed to currents which could spread the sewage material eastward. Immediately offshore from Terminal Island, the black sediments are sandy and contain many broken mollusk shells. The shells may represent a fauna which was killed by the sewage. The sand fraction of the black

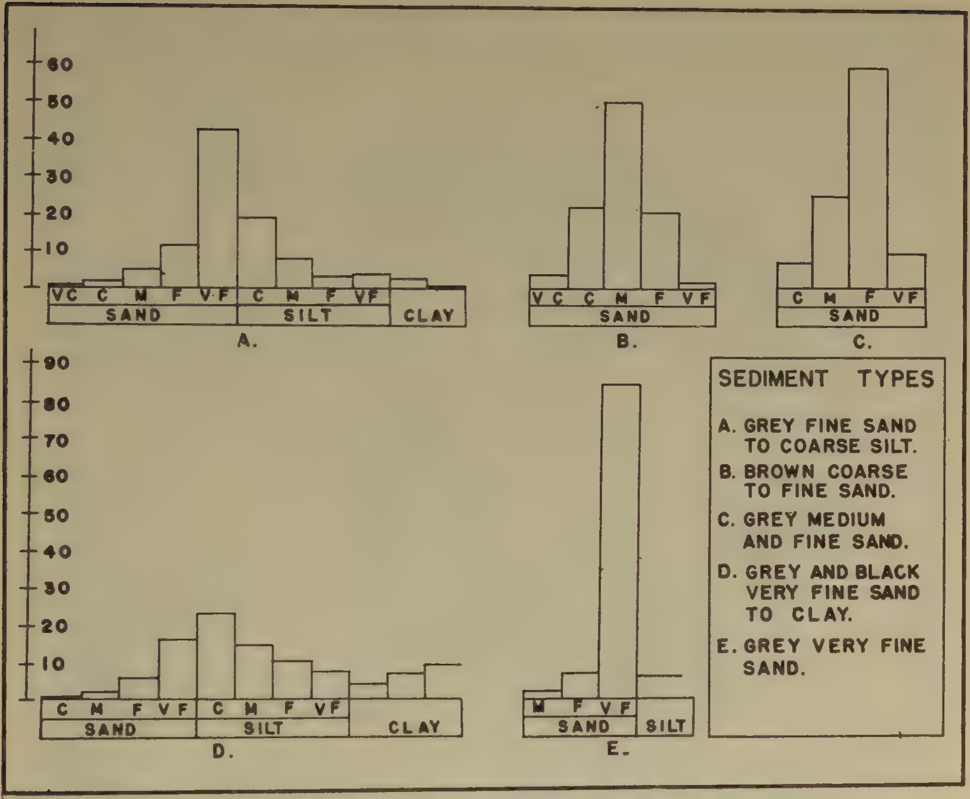


FIG. 5.—Histograms of sediment types.

sand, silt and clay was found to be extremely rich in mica. Some of the quartz and other normally light-colored minerals were dulled by a black organic film.

The black sulphide rich sediments south of Point Fermin are also in a reducing environment. These reducing conditions on the open shelf may be explained by the White's Point sewer outlet two miles west of the sampling area which contributes organic materials to the sediments by means of the prevailing eastward flowing currents.

"Olive drab very fine sand to clay": The area covered by "olive gray very fine sand to clay" amounts to about 7.5 per cent of the total area. Texturally, it is similar to the black sediments, but has a smaller amount of sand and more silt.

Starting at the San Gabriel River mouth and extending northwest for about one mile just offshore, a narrow belt of light brown clay was found superimposed as a thin layer on the normal "gray very fine sand to clay." The longshore currents apparently have carried this distinct brown clay from the river mouth into the breakwater area. No traces of the brown clay layer were found south or east of the river mouth.

A composite sand fraction of the "gray very fine sand to clay" had biotite as the most common mineral followed by quartz, feldspar, and a small amount of hornblende. Rock fragments were also noted in the sand. Most of the grains were angular and pitted, and a few were frosted and subround.

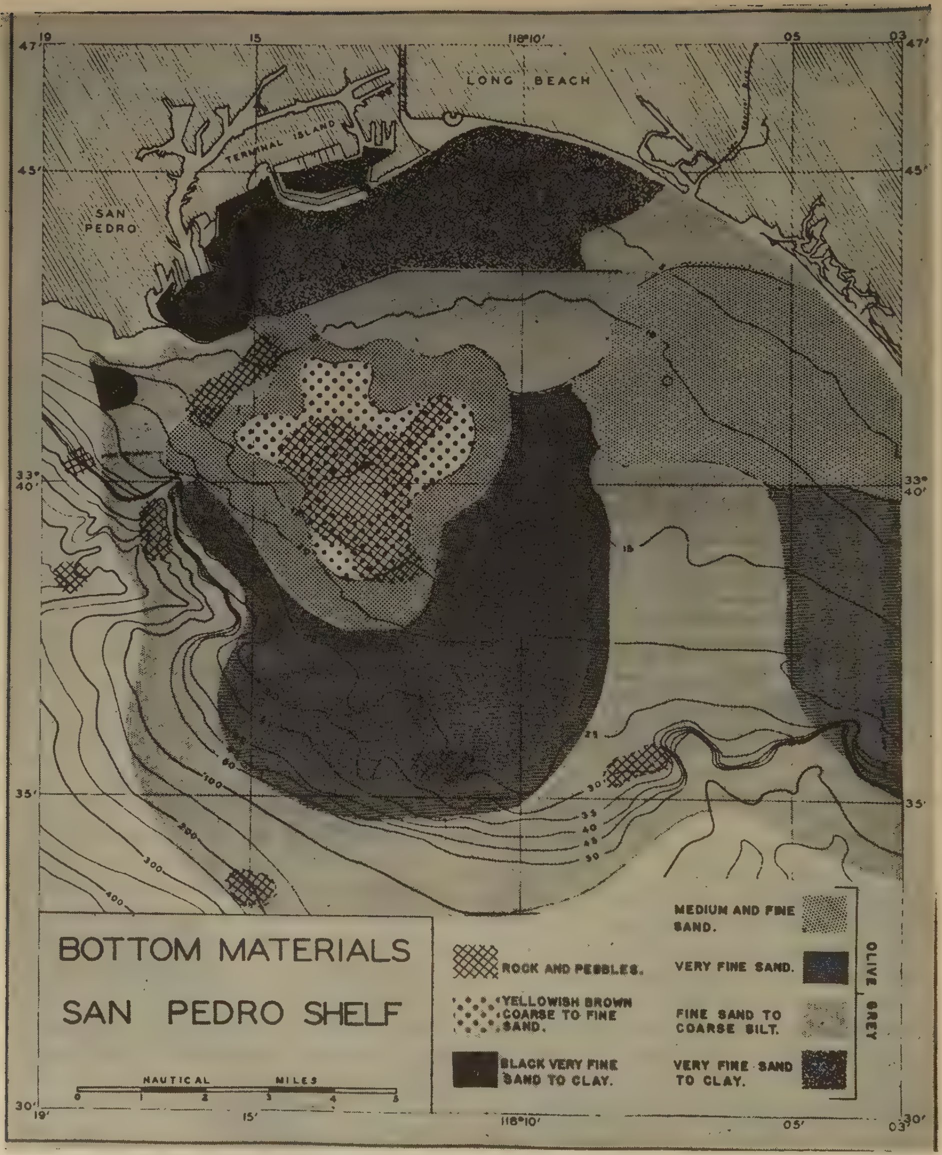

BOTTOM MATERIALS
SAN PEDRO SHELF
NAUTICAL MILES
0 1 2 3 4 5
LONG BEACH
TERMINAL ISLAND
SAN PEDRO
118°10′
47′
45′
33° 40′
35′
30′
19
15
05
03
ROCK AND PEBBLES.
YELLOWISH BROWN COARSE TO FINE SAND.
BLACK VERY FINE SAND TO CLAY.
MEDIUM AND FINE SAND.
VERY FINE SAND.
FINE SAND TO COARSE SILT.
VERY FINE SAND TO CLAY.
OLIVE GREY
15
25
30
35
40
45
50
80
100
200
300
400

Fig. 6.—Bottom materials.

"Olive gray fine sand to coarse silt": By far the most common sediment type is the "olive gray fine sand to coarse silt," which covers approximately 42 per cent of the area sampled, and probably occurs in comparable quantities to the northwest and southeast. The depth limitations of this type are not definitely known as the deeper portions of the escarpment were not sampled thoroughly. A dredge haul at 200 fathoms on the central shelf yielded find sand and silt, but with con-

siderably more silt than is present in this sediment type on the shelf. In the sea valley at the eastern edge of the area, a dredge sample proved to be almost entirely silt and clay, with a negligible amount of sand. This sample was taken in 250 fathoms at the point where the twin valleys join and was on a more gentle slope than the deep sample to the west. From these two deep dredge hauls, showing less sand at 200 and practically no sand at 250 fathoms, the depth distribution of the "olive gray find sand and silt" may be fixed approximately at 200 fathoms.

Textural variations in the "fine sand to coarse silt" are notable. In the area along the south side of the breakwater, it is considerably less well sorted and, in general, has a larger median diameter than it does on the outer shelf. Local concentrations of medium and coarse sand add to the complexity of the belt south of the breakwater. Two of these zones of coarser material were found, one just east of the San Pedro entrance, and the other a mile southwest of the Long Beach breakwater entrance.

Considerably less biotite is present in the "fine sand to coarse silt" than in the "very fine sand to clay" inside the breakwater. Quartz and feldspar are the most common minerals, followed by biotite and hornblende. Very few subrounded grains are present and the material has a fresh appearance.

"*Olive gray very fine sand*": There are two areas of "olive gray very fine sand" which together make up about 25 per cent of the area studied. Texturally, these sands are unique in that they contain on the average more than 80 per cent very fine sand (fig. 5E).

The "very fine sands" consist largely of quartz and feldspar and contain more hornblende than biotite. The grains are angular in shape and show no rounding or frosting.

"*Olive gray medium and fine sand*": Two areas covered by "olive gray medium and fine sand" make up about 18 per cent of the whole sampled area. The ratio of medium to fine sand in these zones is somewhat erratic, but on the average a greater amount of fine sand is present (fig. 5C).

Mineralogically, "the medium and fine sands" most resemble the sand fraction of the finer material within the breakwater, in that some rounded grains are present and there is more biotite than in the very fine sand.

"*Yellowish brown coarse to fine sand*": Most unusual among the sediment types is the "yellowish brown coarse to fine sand" which constitutes the surface layer of about 5 per cent of the area. Unlike the other sediment types, the brown sand is restricted to only one area on the west central shelf where it overlies Miocene shale and limestone and is surrounded by the "olive gray medium and fine sands." Little gradation occurs between the gray and brown sand, and the contact is quite sharp at most localities. A mixture of the two sediment types was found only at four sample stations and these were on the down-current side of the brown sand area. A similar brown sand was noted by Emery, Butcher, Gould, and Shepard (1952) in the San Diego area.

In addition to the striking color contrast which the "yellowish brown coarse to fine sand" presents to the other sediments it is also unique in grain size, composition, shape of grains, and fossil content. The sand has a composition consisting largely of quartz, feldspar, and limestone and shell fragments. Biotite appears to make up only a very small fraction of the sample as does hornblende. Many of the individual grains are polished and smooth, but etching appears on the surface of some of the limestone grains. Subround and subangular grains are more abundant than in any of the other sediment types. The yellowish brown color is in part caused by the many grains of brownish yellow limestone. Iron-stained quartz and feldspar grains also add to the distinctive coloring. Locally the sand is considerably lighter in color as the result of concentrations of mollusk shell fragments, foraminiferal tests, and other shell remains. Although the sand is variable in grain size because of local abundance of granules, rock and shell fragments, its average size distribution shows a modal group within the medium sand range (fig. 5B), and a median diameter which establishes it as the coarsest of the shelf sediments.

Pebble size rock fragments were obtained from nine of the seventeen samples of "yellowish brown coarse to fine sand." These fragments were included in the discussion of rock samples. In view of this anomalous occurrence of pebbles along with the several other features which serve to differentiate it from the remaining sediment types of the shelf, it seems necessary to assign this brown sand to a period of sedimentation other than that which is now in progress. In this respect, the foraminiferal content of the sand is significant. Samples of the sand from 17 localities were examined for foraminifera by R. W. Crouch. Of the 17 samples, 11 were found to contain Pleistocene fauna, and 6 contained Pleistocene and Pliocene species. Only one sample outside of the yellowish brown sand contained Pleistocene Foraminifera, and this was located directly adjacent to the area of brown sand. Crouch believes the fauna of the sands are probably Pleistocene and correlates with the Timms Point formation of Palos Verdes Hills.

The previously discussed "olive gray medium to fine sand" occurs in a wide band around the "yellowish brown sand" and with the exception of a narrow gap extends to the shore on the eastern edge of the area. Because of its position on the shelf and its relative coarseness, it is not inconceivable that this type is relict from a period of more vigorous water circulation.

Texture of Sediments

Grain Size: The size of a sediment at any given locality is generally the result of one, or a combination of several basic factors. These are: (1) distance from shore or source of supply, (2) depth of water, (3) topography of the bottom, and (4) configuration of the coastline, all of which ultimately control the effectiveness of currents and waves as distributing agents. At San Pedro Bay, man-made structures strongly influence coastal configuration.

An attempt to reconcile the sediment distribution on the San Pedro Shelf to the factors influencing grain size reveals some interesting characteristics.

(1) The distance from shore has no apparent effect, when all of the sediments are considered, as the grain size of the sediments on the relatively flat shelf shows no uniform change with increasing distance seaward.

(2) The depth of the water affects grain size only when considerable depth variations exist, or where other factors are not important. Sands on the eastern edge of the shelf show a small change in size as depth increases, but at all other shelf localities the median diameters vary considerably at any given depth, and show no diagnostic change with depth. Great increases in depth such as occur from the shelf to a point some distance down the slope evidently play a part in determining size. A decrease of 49 microns in median diameter occurs between the 25 and 250 fathom contours on the eastern edge of the area.

(3) Topography of the bottom is a difficult factor to analyze in the area of discussion. Large topographic features such as the San Pedro Sea Valley undoubtedly affect sediment size distribution insofar as they deflect waves and currents. The small gentle topographic rises and depressions on the central shelf do not appear to affect grain size: probably because of the residual material at that locality.

(4) The configuration of the coast has a considerable effect on grain size distribution at San Pedro Bay. Old charts, prepared before the construction of the Federal Breakwater, show kelp and rocky bottom in the area east of Point Fermin, and south of the Los Angeles inner harbor entrance. Further inshore, the charts show silt and fine sand, which indicated

that the southeasterly flowing currents were not able to reach far inshore but were quite strong at the deeper rocky localities. At the present time, the regime of the currents is strongly affected by the long breakwater, and the old rocky areas are now covered with fine material, both inside the breakwater and directly adjacent to it on the seaward side. Evidently, the only active currents within the area protected by the breakwater are the northwest flowing longshore currents which enter at the wide gap south of Alamitos Bay. As a result the finest materials of the whole San Pedro Shelf and Escarpment are found in the central part of the area protected by the breakwater.

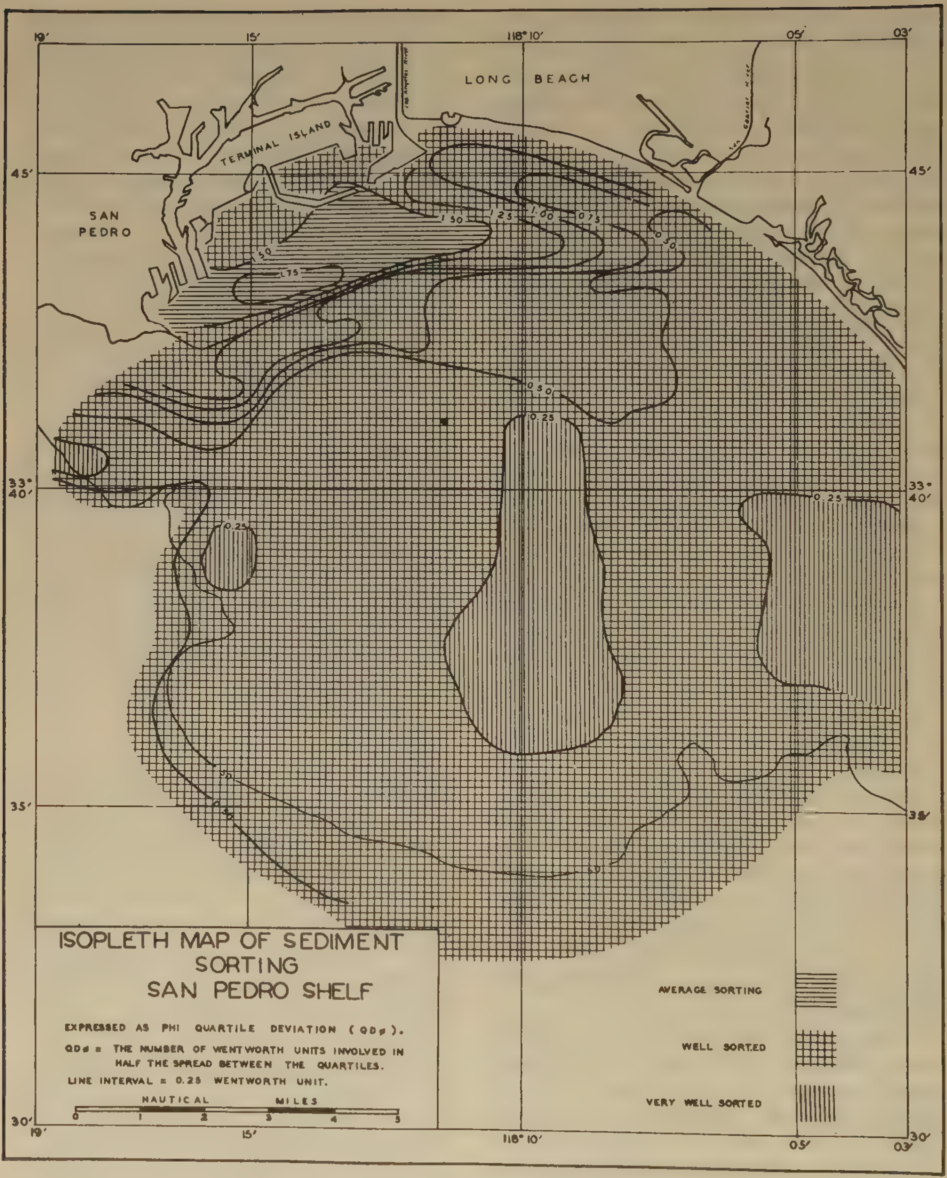
Of the four basic factors above, coastal configuration stands as the most dominant control of waves and currents and hence of grain size distribution. The effects of both distance from shore and depth of water are minimized by this one factor. In addition, the occurrence of the large area of residual yellowish brown sand on the central shelf tends to mask the effects of all of the factors and results in a more random grain size distribution (Emery, 1952).

Sorting: Sorting coefficients of the 75 analyzed samples showed a considerable variation. The units of sorting were calculated in terms of phi quartile deviation, which has the advantage of allowing a direct comparison of samples in terms of the number of Wentworth grades separating the quartiles (Krumbein and Pettijohn, 1938, pp. 232–235).

In order to evaluate the results of the computations, an isopleth map of sediment sorting was prepared (fig. 7). The division between average sorted and well sorted sediments is on the basis of values obtained by Trask. In addition, very well sorted sediments were arbitrarily separated as those having 0.50 or less of a Wentworth grade between the quartiles.

The isopleth map clearly shows the effect of the breakwater in regulating water movement and hence sorting. Poorest sorting is found inside the breakwater in the area of finest sediments where current action is probably sporadic, or lacking. Longshore currents which enter the protected area from the southeast have formed a tongue of well sorted materials extending northwest almost to the mouth of the Los Angeles River. The longshore currents enter the area through the wide gap between the shore and the east end of the breakwater and because of this gap the sediments in the east end of the area north of the breakwater are generally better sorted than those in the west. Seaward and within 2 miles of the breakwater on the western shelf there is a rather rapid change in sorting, but on the shelf beyond sorting is essentially constant. The sediments just outside the breakwater are from one-half to one-sixth as well sorted as those farther out on the shelf. The explanation of this may be that fine material has recently been dredged from inside the breakwater and used to build up the beach just east of Point Fermin. This fine material probably is being removed from the beach by wave action and incorporated into the existing coarser sediments.

Skewness: The phi skewness of each of the analyzed samples was plotted, and a rather complex pattern of skewness resulted. Certain general trends, however, are evident (fig. 8). The most obvious trend is that in nearly all of the sediments within the breakwater the mean of the quartiles lies on the fine side of the median diameter. In other words, the mode, or point of maximum sorting, is coarser than the median diameter. This condition may be the result of fine silt and clay sized particles settling to the bottom in the quiet water which prevails in the outer harbor during much of the year. Occasionally when sufficiently strong waves and currents are generated, coarse silt and sand may be moved from the beaches, or during heavy rains coarse terrestrial material may be introduced. These larger particles, however, settle out according to their size and the velocity of the currents in such a way that at any given locality there is a greater concen-



19′
15′
118° 10′
05′
03′
LONG BEACH
Los Angeles River
San Gabriel River
TERMINAL ISLAND
SAN PEDRO
45′
33° 40′
35′
30′
1.50
1.25
1.00
0.75
0.50
0.25
ISOPLETH MAP OF SEDIMENT SORTING SAN PEDRO SHELF
EXPRESSED AS PHI QUARTILE DEVIATION (QDφ).
QDφ = THE NUMBER OF WENTWORTH UNITS INVOLVED IN HALF THE SPREAD BETWEEN THE QUARTILES.
LINE INTERVAL = 0.25 WENTWORTH UNIT.
NAUTICAL MILES
0 1 2 3 4 5
AVERAGE SORTING
WELL SORTED
VERY WELL SORTED

FIG. 7.—Isopleth map of sediment sorting.

tration of material of essentially one size. Sediments with positive phi skewness are also found just outside of the breakwater in the western part of the area. It is questionable, however, that the above explanation for the positive skewness would be applicable to this area, since no restrictions on water movements are present.

Figure 8 also shows that most of the

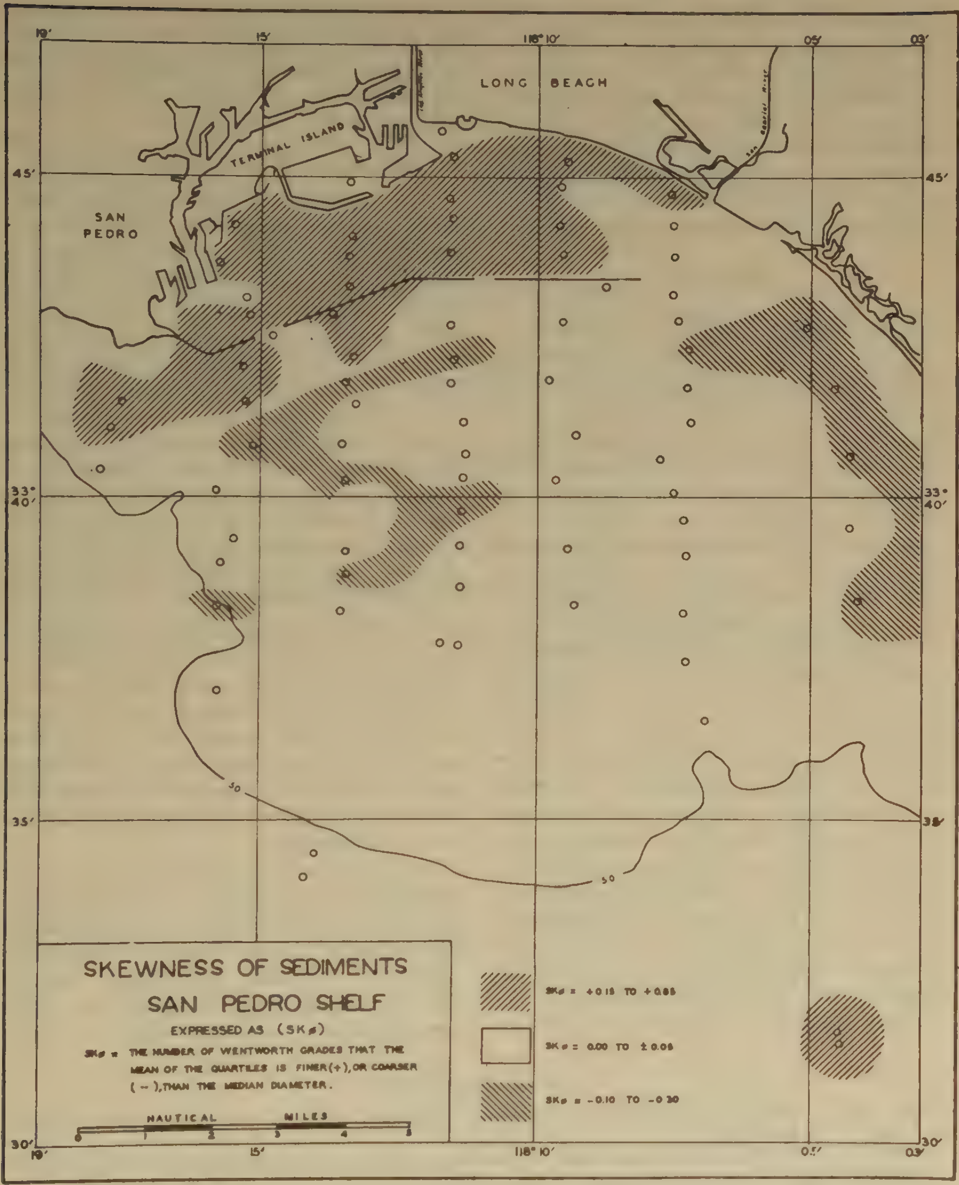

19′
15′
118° 10′
05′
03′
45′
33°
40′
35′
30′
LONG BEACH
TERMINAL ISLAND
SAN PEDRO
50
SKEWNESS OF SEDIMENTS
SAN PEDRO SHELF
EXPRESSED AS (SKφ)
SKφ = THE NUMBER OF WENTWORTH GRADES THAT THE MEAN OF THE QUARTILES IS FINER(+), OR COARSER (−), THAN THE MEDIAN DIAMETER.
NAUTICAL MILES
0 1 2 3 4 5
SKφ = +0.15 TO +0.85
SKφ = 0.00 TO ±0.05
SKφ = −0.10 TO −0.30

FIG. 8.—Skewness of sediments.

sediments on the shelf area, seaward of the breakwater, have negligible skewness. The exceptions are two areas of negative skewness; one along the eastern edge of the area adjacent to the unprotected beaches, and the other on the central shelf in the vicinity of the coarsest shelf sediments. The negative phi skewness indicates that the modal size group lies to the fine side of the median diameter. In the case of the sediments adjacent to the beach, this distribution could be brought about by the nearness of the large supply of relatively coarse sands which form the beaches along this segment of coast. A similar situation prevails at the central shelf locality where very coarse to coarse sands and shell fragments may be shifted into a deposit of normally finer material.

CONCLUSIONS

Significance of Bedrock Exposures

Exposures of middle Miocene, late Miocene, and early Pliocene bedrock are found flanked by unconsolidated sediments at widely scattered localities on San Pedro Shelf and Escarpment. This widespread distribution of outcrops on the seafloor indicates the presence of an unconformity which is now only partially covered with a relatively thin layer of late Pleistocene to Recent sediments.

In general the rocks of the shelf and its bordering escarpment appear to be essentially the same in lithology and sequence as those forming the structural highland of the Palos Verdes Hills on the coast northwest of the shelf. The ages together with the localities and depths from which some of the rocks were collected suggest a southeastward trending anticlinal submarine extension of the structural unit of the Palos Verdes Hills. Middle Miocene rocks crop out at depths of from 60–80 feet on the central shelf, whereas early Pliocene exposures occur at depths of about 1,200 feet on the slope at the southern boundary of the area. Oil wells on Terminal Island just north of the area, are drilled in the south flank of the Wilmington Anticline and show the early Pliocene to be at depths of over 2,500 feet.

Significance of Sediment Studies

Size analysis of representative sediment samples show that the finest material of the entire San Pedro Shelf and its slope (very fine sand to clay) occurs in the area enclosed by the Federal Breakwater in the northern part of the sampled area which acts as a man made settling basin. The coarsest material is a yellowish brown sand which lies 3 to 5 miles offshore on the west central shelf flanking the middle Miocene rocks at that locality. This sand is evidently residual from a seaward extension of the poorly consolidated Pleistocene sands which lap up against the north and east flanks of the Palos Verdes Hills.

Elsewhere on the shelf the sediments consist of areas of olive grey medium to fine sand, very fine sand, and fine sand to coarse silt. All of these are considered to be recent sediments, with the possible exception of the medium to fine sand which because of its relative coarseness may be relict from a period of more active water circulation.

Sediment sorting within the area correlates well with known current patterns. Sorting is excellent to good on the entire shelf except near the Federal Breakwater where it becomes noticeably poorer. Poorest sorting occurs inside the breakwater within the outer harbor.

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Sea Temperature in the Marshall Islands Area

By MARGARET K. ROBINSON

Bikini and Nearby Atolls, Marshall Islands

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-D

DEPARTMENT OF THE INTERIOR
March 3, 1849

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CONTENTS

	Page
Abstract	281
Introduction	281
Distribution of bathythermograms	281
Method of analyzing data	285
Horizontal distribution of temperature	285
Smoothed average-annual-temperature curves	286
Vertical sections of temperature across the equatorial currents	288
Temperature distribution in 1-degree square surrounding Bikini Atoll	288
Literature cited	291

ILLUSTRATIONS

[Plates 74–79, in pocket]

		Page
PLATES 74–77.	Average temperatures, at surface and at depth.	
74.	January, February, March, and April.	
75.	May, June, July, and August.	
76.	September, October, November, and December.	
77.	Maximum, minimum, range, and annual.	
78–79.	Vertical sections of temperature.	
FIGURES 94–96.	Distribution of bathythermograph observations.	
94.	Total	282
95.	January–June	283
96.	July–December	284
97.	Annual-temperature curves for 5-degree squares, at surface and at depth	287
98–99.	Average temperature of water surrounding Bikini Atoll, at surface and at depth	289–290

TABLES

		Page
TABLE 1.	Time distribution of bathythermograms, by years	282
2.	Time distribution of bathythermograms, by months	282

BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

SEA TEMPERATURE IN THE MARSHALL ISLANDS AREA

By Margaret K. Robinson

ABSTRACT

Horizontal distribution of average sea temperature, based on 6,766 bathythermograms in the Marshall Islands area, 20° N.–5° S., 155° E.–175° W. is presented in charts of average temperature for each month, for the surface and for the 200-, 300-, and 400-foot levels, together with charts of maximum, minimum and range of average monthly temperatures and the annual average for the same depths. Analysis of the temperature distribution shown on these charts indicates that there are two major seasonal regimes: a summer regime from April to August, characterized at 400 feet by large-scale cold cells on both sides of the Marshall and Gilbert Islands chain; a winter regime from October to February, characterized at the same depth by a tongue of cold water, at about 8° N., which runs directly across the area. Certain conclusions concerning the currents can be drawn from the pattern of isotherms shown on the horizontal charts. The Marshall and Gilbert Islands chain appears to be a topographical barrier across the Equatorial Current system giving rise to large-scale eddies in the North Equatorial Current, the Equatorial Countercurrent, and possibly the South Equatorial Current. There are evidently seasonal changes in the position of the currents and in the formation of the eddies. There appears to be an eastward flow north and west of the Marshall Islands.

Smoothed average-annual-temperature curves for each 5-degree square in the area are presented for the surface and for depths of 100, 200, 300, 350, and 400 feet. The annual curves show seasonal cycles not immediately apparent in the horizontal charts. North of 10° N. there is a single annual cycle for the surface and the 100- and 200-foot curves. South of 10° N. a double temperature cycle develops in the same levels. This double cycle is also seen in some 5-degree squares south of the equator. The curves for the lower levels, which are associated with the depth of the thermocline, frequently show inverse relationships with the surface curves.

Fourteen vertical sections of temperature across the Equatorial Currents, based on individual bathythermograph observations, between Longitudes 163° E. and 120° W., are given. These sections show that there are marked differences in the width of the Equatorial Countercurrent and in the depth of the thermocline in the current boundary zones, going from east to west across the Pacific Ocean; and that temperatures inimical to coral reef growth in the Eastern Pacific are found in the euphotic zone.

Charts of temperature distribution at two different times in the 1-degree square surrounding Bikini Atoll for the surface, and for the 200-, 300-, 400-, 600-, and 800-foot levels are shown. These charts illustrate possible deviations from the average values of the monthly charts which might be expected within a 1-degree square.

INTRODUCTION

In order to provide an average environmental background of ocean temperature for the scientific research in biology and geology done at Bikini Atoll and in the Marshall Islands, this analysis of 6,766 bathythermograms for the area latitude 20° N. to 5° S., longitude 155° E. to 175° W. has been made. The average-temperature distributions based on this analysis can also be used to make qualitative inferences about the ocean currents in the area.

Temperature and salinity data obtained from Nansen bottles and reversing thermometers in the Marshall Islands are insufficient for a detailed picture—of such importance to the biologist—of the surface layers of the sea at depths of less than 400 feet. On the other hand, the accuracy of reversing thermometers cannot be claimed for bathythermograph readings. In the oceanic area between Hawaii and California average temperatures based on these readings were shown to have a positive bias of 1.0° F in comparison with temperatures measured with reversing thermometers.[1] The amount of bias in the readings for this area has not been accurately ascertained, but visual comparison of the temperature distribution in this study with that based on reversing thermometer measurements (Barnes, Bumpus, and Lyman, 1948, and Mao and Yoshida, 1954) will show the temperatures of this study also to be warmer on the average by approximately 1.0° F. However, average temperatures based on bathythermograms give excellent relative pictures of temperature distribution at constant level or in vertical sections, and absolute temperature values can be inferred from comparisons with accurate reversing-thermometer data.

The author wishes to express thanks and appreciation to Dr. Roger Revelle for his personal assistance and beneficial criticisms during the preparation of this temperature study.

DISTRIBUTION OF BATHYTHERMOGRAMS

This study is based on 6,766 individual bathythermograph readings taken by U. S. Navy and U. S. Coast

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Note.—Contribution from The Scripps Institution of Oceanography, New Series No. 700.

[1] Robinson, M. K., 1951, Sea Temperature in the North Pacific Area, lat. 20°–40°. N., long. 125°–155° W.: Scripps Inst. Oceanography, Reference 51–20, September 15, 1951.

Reproduced, by permission, from U.S. Geological Survey, Professional Paper 260-D, 1954.

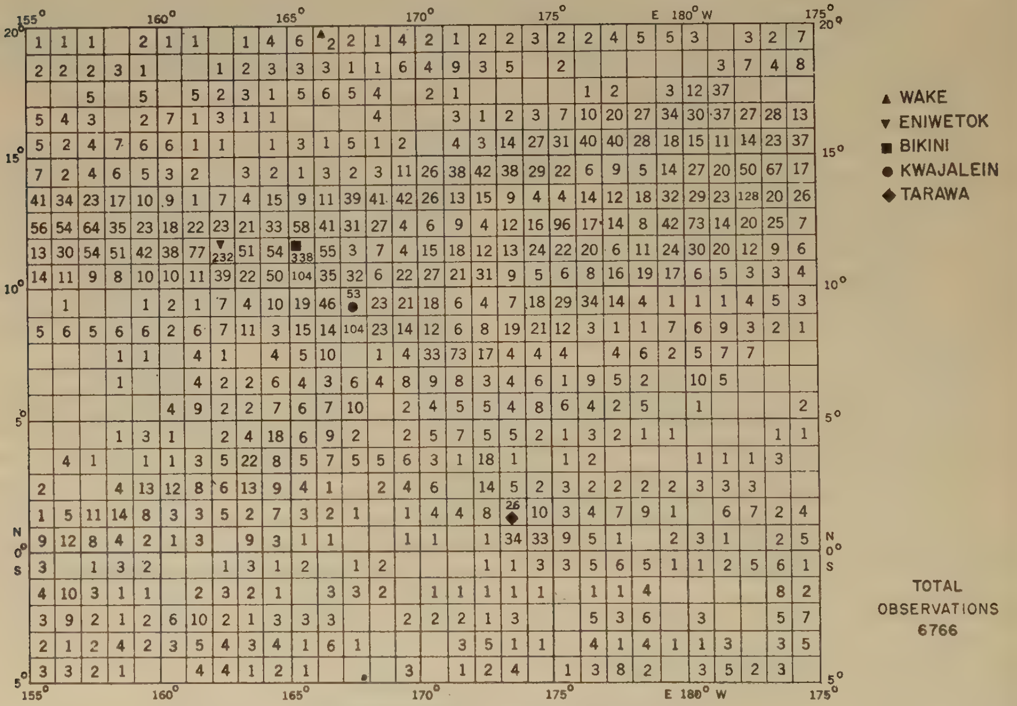
Guard ships between 1942 and 1951. These bathythermograms—the photographic reproductions of the original glass slide used in the bathythermographs—are on file at the Scripps Institution of Oceanography. Figure 94 gives the total space distribution of the observations; figures 95 and 96 give the space distribution by months. In table 1 the time distribution of the data in percentages by years has been tabulated; in table 2 the time distribution is given in percentages by months.

TABLE 1.—*Time distribution of bathythermograms, by years*

Year	Percent	Year	Percent	Year	Percent
1942	0.3	1946	7	1949	0
1943	1.7	1947	3	1950	2
1944	49	1948	3	1951	2
1945	32				

TABLE 2.—*Time distribution of bathythermograms, by months*

Month	Percent	Month	Percent	Month	Percent
January	4	May	5	September	9
February	8	June	11	October	6
March	12	July	10	November	21
April	8	August	12	December	6



1	1	1		2	1	1		1	4	6	▲ 2	2	1	4	2	1	2	2	3	2	2	4	5	5	3		3	2	7
2	2	2	3	1			1	2	3	3	3	1	1	6	4	9	3	5		2						3	7	4	8
		5		5		5	2	3	1	5	6	5	4		2	1					1	2		3	12	37			
5	4	3		2	7	1	3	1	1				4			3	1	2	3	7	10	20	27	34	30	37	27	28	13
5	2	4	7	6	6	1	1		1	3	1	5	1	2		4	3	14	27	31	40	40	28	18	15	11	14	23	37
7	2	4	6	5	3	2		3	2	1	3	2	3	11	26	38	42	38	29	22	6	9	5	14	27	20	50	67	17
41	34	23	17	10	9	1	7	4	15	9	11	39	41	42	26	13	15	9	4	4	14	12	18	32	29	23	128	20	26
56	54	64	35	23	18	22	23	21	33	58	41	31	27	4	6	9	4	12	16	96	17	14	8	42	73	14	20	25	7
13	30	54	51	42	38	77	▼ 232	51	54	■ 338	55	3	7	4	15	18	12	13	24	22	20	6	11	24	30	20	12	9	6
14	11	9	8	10	10	11	39	22	50	104	35	32	6	22	27	21	31	9	5	6	8	16	19	17	6	5	3	3	4
	1			1	2	1	7	4	10	19	46	53 ●	23	21	18	6	4	7	18	29	34	14	4	1	1	1	4	5	3
5	6	5	6	6	2	6	7	11	3	15	14	104	23	14	12	6	8	19	21	12	3	1	1	7	6	9	3	2	1
			1	1		4	1		4	5	10		1	4	33	73	17	4	4	4		4	6	2	5	7	7		
			1			4	2	2	6	4	3	6	4	8	9	8	3	4	6	1	9	5	2		10	5			
					4	9	2	2	7	6	7	10		2	4	5	5	4	8	6	4	2	5		1				2
			1	3	1		2	4	18	6	9	2		2	5	7	5	5	2	1	3	2	1	1				1	1
	4	1		1	1	3	5	22	8	5	7	5	5	6	3	1	18	1		1	2				1	1	1	3	
2			4	13	12	8	6	13	9	4	1		2	4	6		14	5	2	3	2	2	2	2	3	3	3		
1	5	11	14	8	3	3	5	2	7	3	2	1		1	4	4	8	26 ◆	10	3	4	7	9	1		6	7	2	4
9	12	8	4	2	1	3		9	3	1	1			1	1		1	34	33	9	5	1		2	3	1		2	5
3		1	3	2			1	3	1	2		1	2				1	1	3	3	5	6	5	1	1	2	5	6	1
4	10	3	1	1		2	3	2	1		3	3	2		1	1	1	1	1		1	1	4					8	2
3	9	2	1	2	6	10	2	1	3	3	3			2	2	2	1	3			5	3	6		3			5	7
2	1	2	4	2	3	5	4	3	4	1	6	1				3	5	1	1		4	1	4	1	1	3		3	5
3	3	2	1			4	4	1	2	1				3		1	2	4		1	3	8	2		3	5	2	3	

FIGURE 94.—Distribution of bathythermograph observations—total.

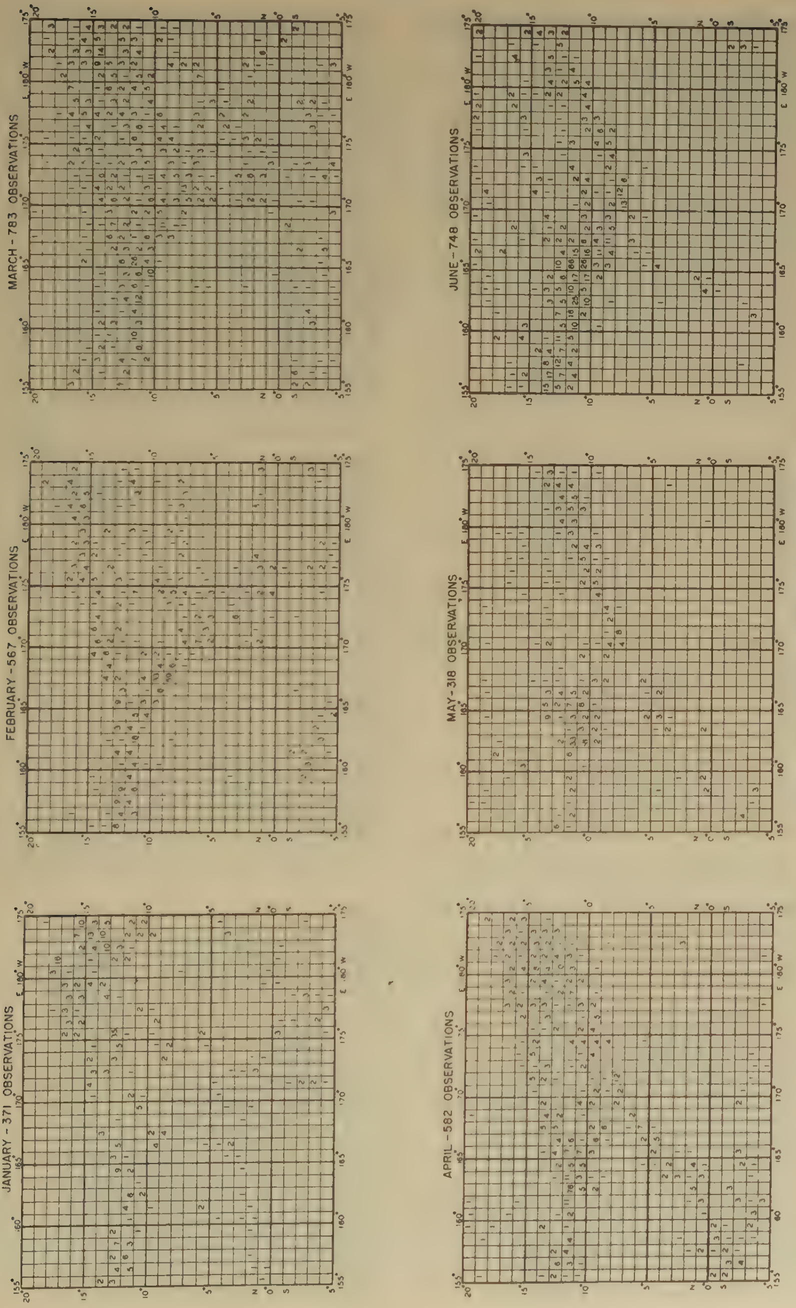

JANUARY - 371 OBSERVATIONS
FEBRUARY - 567 OBSERVATIONS
MARCH - 783 OBSERVATIONS
APRIL - 582 OBSERVATIONS
MAY - 318 OBSERVATIONS
JUNE - 748 OBSERVATIONS
20°
15°
10°
5°
N 0° S
5°
175°
E 180° W
175°
170°
165°
160°
155°

FIGURE 95.—Distribution of bathythermograph observations—January–June.

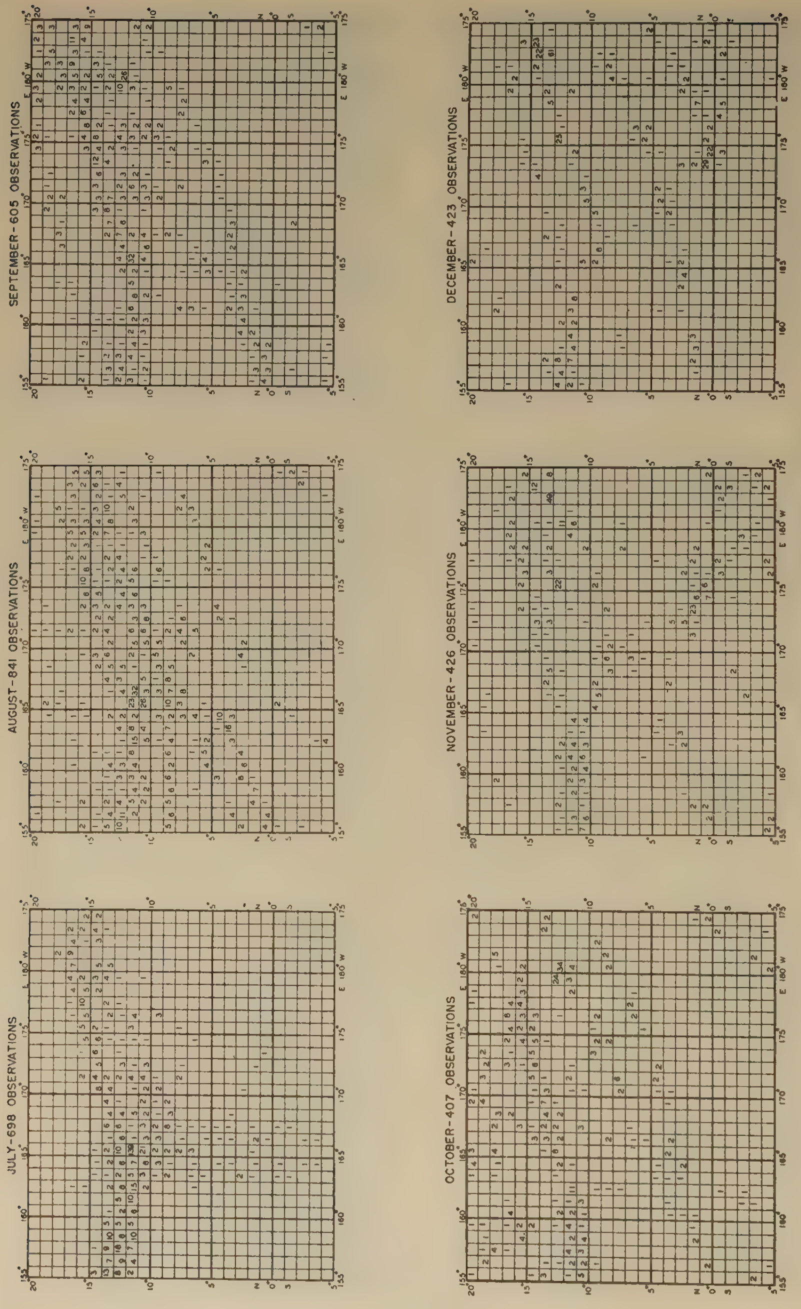

SEPTEMBER-605 OBSERVATIONS
AUGUST-841 OBSERVATIONS
JULY-698 OBSERVATIONS
DECEMBER-423 OBSERVATIONS
NOVEMBER-426 OBSERVATIONS
OCTOBER-407 OBSERVATIONS
175°
E 180° W
175°
170°
165°
160°
155°
20°
15°
10°
5°
N 0° S
5°

FIGURE 96.—Distribution of bathythermograph observations—July-December.

METHOD OF ANALYZING DATA

Temperatures at the surface and at depths of 100, 200, 300, 350, and 400 feet were read from all bathythermograms, averaged arithmetically by months and by 1-degree squares and entered on base maps of the area. Next, all values for each level within each 5-degree square (twenty-five 1-degree squares) were averaged by months and plotted against time. Smooth annual curves for each level and for each 5-degree square were drawn (fig. 97). In several squares, where no data are available for certain months, this required considerable interpolation. The annual curves were checked for consistency by comparing them from level to level and by drawing for each month an average temperature-depth curve from the annual curve values of each 5-degree square. Values for each 5-degree square for each month and depth were then read from the annual curves and entered on transparent sheets, which were used as overlay sheets for charts on which the average values for 1-degree squares had been entered. The first drawing of the isotherms was made on these overlay sheets. Contours were based on the average values for 1-degree squares where available; where these are lacking, the average values for 5-degree squares from the annual curves were used. In the final draft, minor irregularities based on values for 1-degree squares were smoothed out when they appeared to be inconsistent with the over-all picture.

Plates 74, 75, and 76 present the horizontal temperature distribution by months. Dashed lines (based on 5-degree squares) have been used to indicate where the isotherms are based on values from the annual curves shown in figure 97. Solid lines indicate values based on one-degree squares. The 100-foot and 350-foot charts were eliminated from the final results; values for these levels, however, are included in the annual curves (fig. 97).

Plate 77 comprises four charts showing average temperatures: the maximum average; the minimum average; the range of the average; and the annual average. These four charts are based on the averages for 5-degree squares.

HORIZONTAL DISTRIBUTION OF TEMPERATURE

There are several prominent features in the horizontal distribution charts which reflect the presence of the North and South Equatorial Currents and the Equatorial Countercurrent, as well as the effect of the topographic barrier across the current systems presented by the Marshall and the Gilbert Islands.

Two major seasonal regimes are evident in the horizontal distribution charts: a summer regime from April to August, a winter regime from October to February. March and September are transition months.

These seasonal differences can best be seen by comparing the 400-foot charts of the different months. At this depth the winter regime is characterized by a tongue of cold water, its axis usually at about 8° N., which runs directly across the area from December to March, but which has a saddle point near the Marshall Islands from September to November. During these months the tongue has a slight southwest trend east of the Marshall Islands. From September to December there is a warm tongue whose axis points northeast through the gap between the Marshall and the Gilbert Islands from south of the equator at 155° E. longitude. In the vicinity of the Gilbert Islands, from September to December, the isotherms bend around to form a cold tongue near the equator. North and west of the Marshall Islands, from September to February, there is a warm tongue near 15° N. whose trend is approximately eastward. North of this tongue there is a considerable decrease in temperature in the vicinity of Wake Island.

Beginning with April we see a greatly different pattern at the 400-foot depth level. There is a wedge of warm water west of the Gilbert Islands extending north of the Marshall Islands which divides the southern part of the area into two large cold cells. In some months the colder water appears within the western cell, in others within the eastern cell. During these months, as in winter, we find a warm tongue north and west of the Marshall Islands, with decreasing temperatures near Wake Island.

The surface charts differ markedly in appearance from the 400-foot charts, chiefly because the range of temperature at the surface is much smaller than at 400 feet. But there are also important differences in the pattern of the isotherms.

At the surface from September through March we find a warm tongue from the southwest whose axis extends directly through the island gap and also a tongue of cooler water from the northeast whose axis generally parallels that of the warm tongue. But while the effects of the warm tongue usually are evident beyond the gap between the Marshall and the Gilbert Islands, the cool tongue tends to be blocked by the Marshall Islands. Inspection will show that these surface features are displaced relative to their counterparts at 400 feet. During the northern winter there is also a cool tongue in the southeast whose axis shifts north and south of the equator, but whose approach is usually directly from the east. At times the axis is directed through the Gilbert Islands, at other times it is deflected to the north or south, and in the month of January the tongue terminates east of the Gilbert Islands. This tongue is better defined in the surface charts than in the 400-foot charts. It is interesting to note that in December the coldest water in the entire area at the surface is at the equator at 175° W. longitude. This cool water appears to be associated with divergence in the South Equatorial Current. Contrary to expectations, it is not evident across the entire area. The warm tongue north and west of the Marshall Islands shown on the 400-foot charts is also evident at the surface during the winter months, but it is more variable in position and trend than at 400 feet.

This warm tongue is also present at the surface during certain summer months. The main difference between the summer and winter regimes at the surface is that in summer the warm tongue from the southwest is poorly defined and variable. This warm tongue, which also can be seen in the lower-level charts, is thought to be associated with convergence between the Equatorial Countercurrent and the South Equatorial Current, and the cool tongue from the northeast is thought to be associated with divergence between the Equatorial Countercurrent and North Equatorial Current.

The 200-foot charts are very similar to the surface charts because the thermocline is generally below this level throughout the area. However at 300 feet marked changes begin to occur due to differences in thermocline depth within the area, the full effect of which is seen on the 400-foot charts described above.

Certain conclusions concerning the currents can be drawn from the pattern of isotherms shown on the horizontal charts. The Marshall and the Gilbert Islands chain appears to be a topographical barrier across the Equatorial Current system giving rise to large-scale eddies in the North Equatorial Current and the Equatorial Countercurrent. There are evidently seasonal changes in the position of the currents and in the formation of eddies. During some months the Equatorial Countercurrent appears to flow directly through the gap between the islands. The diagonal trend of the isotherms associated with the Equatorial Countercurrent confirms the opinion of Sverdrup, Johnson, and Fleming (1942), and Mao and Yoshida (1954) that the Equatorial Countercurrent may be found on both sides of the equator. During some months the South Equatorial Current appears to flow to the north of the Gilbert Islands, in other months to the south of them. The tongue of cool water at the equator associated with this current goes beyond the islands in some months, but appears to be stopped by them in others, indicating an eddy also in the South Equatorial Current. The warm water north and west of the Marshall Islands appears to be associated with an eastward flow found by Barnes, Bumpus, and Lyman (1948), and Mao and Yoshida (1954).

The charts on plate 77 show, respectively, the maximum, the minimum, and the range of average monthly temperatures and the annual average. Along the island chains the average range of temperature at and above 300 feet is only about 3° F. Because of the shifting depth of the thermocline, the range at 400 feet is much greater, rising to 10° F. in the southern Marshall Islands.

SMOOTHED AVERAGE-ANNUAL-TEMPERATURE CURVES

In figure 97 are presented smoothed average-annual-temperature curves for each of the thirty 5-degree squares in the area. As shown in figures 95 and 96 the numbers of observations on which these curves are based differ widely. For example, the curves for the three 5-degree squares between 10°–15° N., 155°–160° E., 160°–165° E. and 165°–170° E. contain practically no interpolations or smoothing, while the lower levels of the three 5-degree squares from 0°–5° S., east of 170° E. are based upon very few observations and should be considered as a first approximation only. Where a large number of observations were available, year-to-year variation and individual erratic values would be eliminated from the curves.

Annual-temperature curves show seasonal cycles not immediately apparent in the horizontal charts. North of 10° N., these curves show a single annual cycle for the surface, and at 100 and 200 feet, with minimum temperatures in February and March and maximum temperatures in September and October. However, in several squares the temperatures do not increase continuously from March to October but remain nearly constant in June, July and August.

Between 5° and 10° N., the leveling off in June and July in the upper levels above the thermocline becomes a double cycle with secondary maxima and minima. Just as there is a lag in the maximum temperature in the north from the time the sun is at its most northerly position, there are also marked differences in phase at these latitudes between the sun's passage and the times of maximum and minimum temperatures. A double cycle is also found in some squares south of the equator. The two 5-degree squares, 0°–5° N., 155°–160° E., and 0°–5° S., 155°–160° E., show an anomalous one-cycle curve above the thermocline with minimum temperatures in June and maximum temperatures in October. The annual range of temperature at the surface is only 2.8° F, and here the highest temperatures of the entire area are found throughout the year. In this area of minimum annual range of temperature the effects of the shifting position of the Equatorial Countercurrent completely overshadow the effects of the sun's passage.

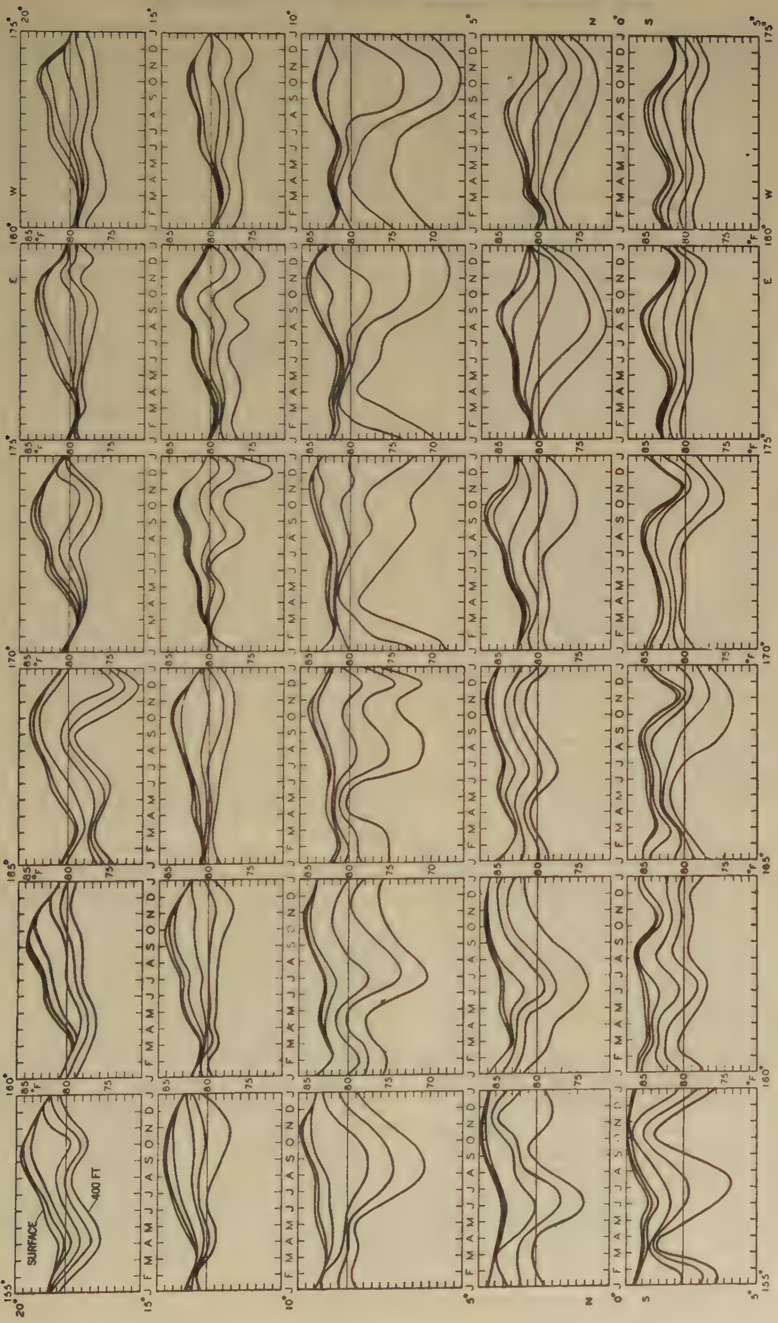


FIGURE 97.—Annual-temperature curves for 5-degree squares at the surface and at depths of 100, 200, 300, 350, and 400 feet.

Temperatures at 300, 350, and 400 feet are related primarily to the depth of the thermocline and the curves for these depths frequently show inverse relationships with the surface curves. The 5-degree square, 15°–20° N., 170°–175° E., is an example. In this square the thermocline is below 400 feet in February and March and near 200 feet late in summer.

The curves of the lower levels between 5° and 10° N. and, to some extent, from 0° to 5° N. show the dramatic results of the shallow thermoclines in the transition zone between the North Equatorial Current and the Equatorial Countercurrent. It is regrettable that the data upon which these curves were based were not so complete as those north of 10° N. It is thus not possible to say to what extent these curves represent the average or typical position of the currents or how much they may be biased by the distribution of the data, the year-to-year variation, internal waves, and observational errors.

From 0°–5° S. very few data were obtained in the lower levels east of the Gilbert Islands, and these curves, which tend to parallel the surface curves, may not be valid; however, in the horizontal charts, the temperature distribution based on these values appears to be consistent with the surrounding values. The three 5-degree squares west of the Gilbert Islands were based on more data but are quite different one from another. If the shapes of these curves, which are represented as a first approximation, are found to be typical on the basis of additional data, their differences can be explained only as results of the shifting currents.

VERTICAL SECTIONS OF TEMPERATURE ACROSS THE EQUATORIAL CURRENTS

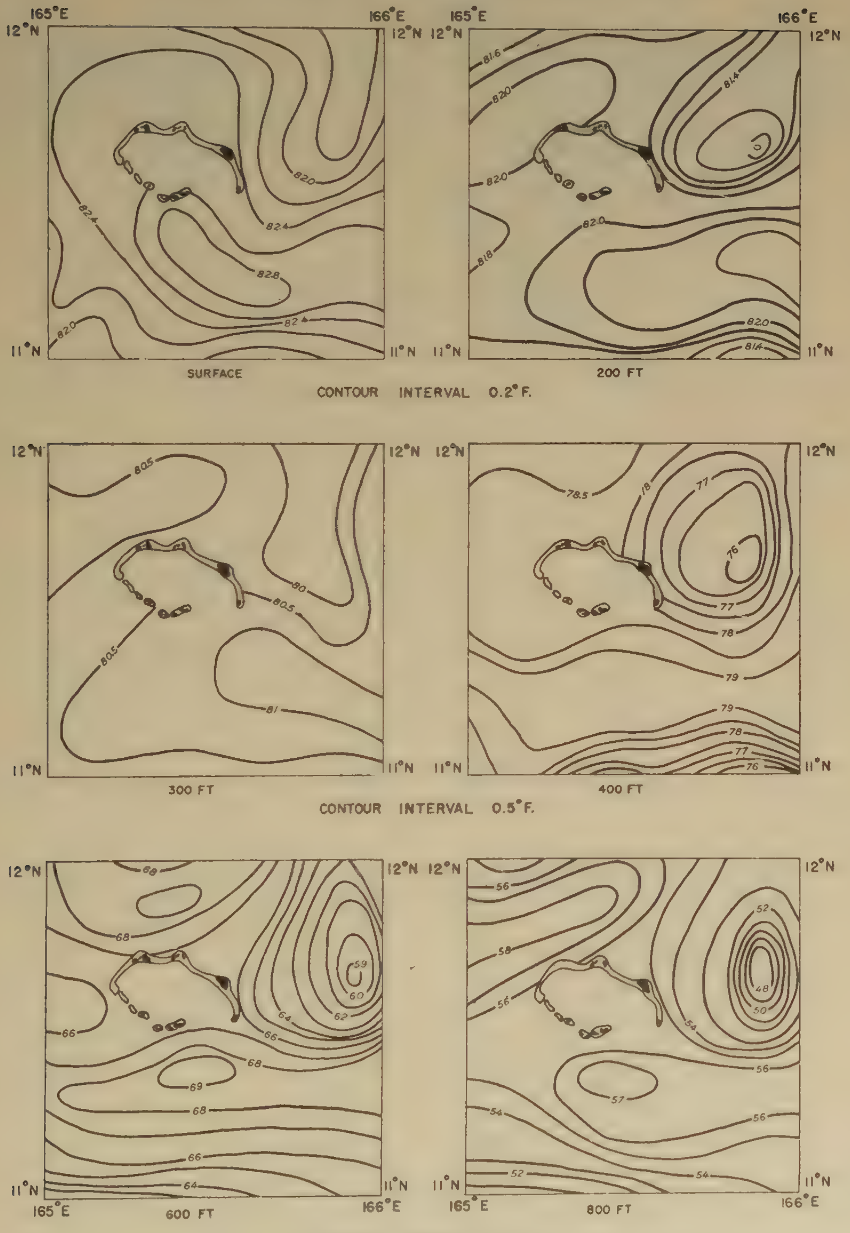
Fourteen vertical sections of temperature, based on individual bathythermograms, have been selected to show differences with longitude. All sections are presented on the same latitude and depth scale. Plate 78 shows vertical-temperature sections based on observations taken aboard the U. S. S. *Barton*, U. S. S. *O'Brien*, U. S. S. *Laffey*, and U. S. S. *Blish* during Operation Crossroads. These records were the only ones available within the Marshall Islands area. The remaining sections in plate 78 and that given in plate 79*B* are based on observations taken aboard the Fish and Wildlife Service Motor Vessels *Hugh M. Smith* and *John R. Manning* by the Pacific Oceanic Fisheries Investigations of the U. S. Fish and Wildlife Service under the direction of Townsend Cromwell. Plate 78 shows two sections, at longitude 172° W., giving differences between February and July of 1950 at this location; other sections in plate 78 and the section in plate 79*B* give the differences for the same period at longitude 158° W.

Observations given in plate 79 *A* and *D* were made from U. S. Navy ships on wartime missions. Plate 79*C* is based on observations made aboard the U. S. C. G. C. *Northwind* while returning from Operation Highjump in the Antarctic. Plate 79*E* and *F* is based on observations taken during the Scripps Institution–U. S. Navy Electronics Laboratory Mid-Pacific Expedition of 1950. Plate 79*G* and *H* is based on observations taken by U. S. Navy Electronics Laboratory personnel aboard the U. S. S. *Serrano*. In plate 79 the sections cross the currents diagonally as indicated by the longitude stations given on the plate.

Although internal waves introduce many irregularities into the depth of the thermocline and the isotherms, in general the depth of the thermocline decreases northward from about latitude 3° to latitude 5° N., reaches a minimum depth between latitudes 6° and 10° N., then increases in depth again to the north. To the south of the region of minimum thermocline depth, or current boundary zone, the Equatorial Countercurrent flows east; to the north the North Equatorial Current flows west. South of latitudes 3° to 5° N. the thermocline depth also decreases, but in this region of the South Equatorial Current the thermocline depths remain greater than in the boundary zone to the north. Marked differences are seen in the sections from west to east, particularly in the width of the Equatorial Countercurrent and in the thermocline depth in the current boundary zone. However, of particular interest to the geologist and biologist is the presence of temperatures inimical to the growth of coral reefs in the euphotic zone in the eastern Pacific and the absence of these cold temperatures in the euphotic zone in the western Pacific.

TEMPERATURE DISTRIBUTION IN 1-DEGREE SQUARE SURROUNDING BIKINI ATOLL

Figures 98 and 99 are based on the 900-foot bathythermograph observations taken during Operation Crossroads. Figure 98 gives an average picture of the observations taken from May 8th to July 9th, and figure 99 is based on observations taken between July 20th and August 4th. It should be noted that the contour interval at the surface and at 200 feet is 0.2° F; at 300 and 400 feet it is 0.5° F, and at 600 and 800 feet it is 1.0° F. The temperature range within this area above the thermocline ranges from 1° F to 3° F, but below the thermocline it increases to 10° F. These charts are included to indicate the possible deviation from the average values of the isotherms in the horizontal charts (pls. 74, 75, 76) which can be expected for individual observations within a 1-degree square.

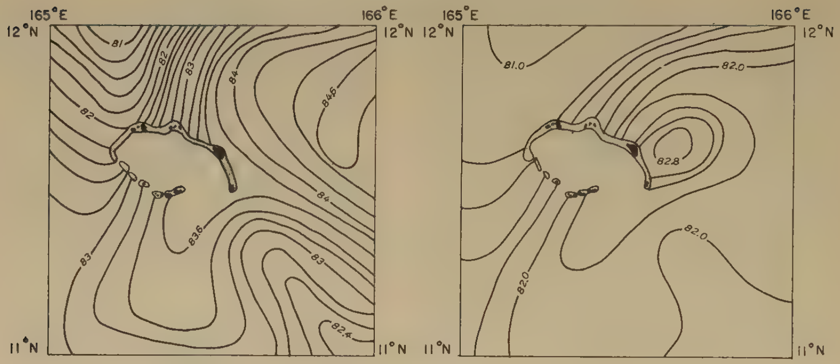

165°E
166°E
12°N
11°N
82.0
82.4
82.8
82.4
82.0
SURFACE
81.6
82.0
82.0
81.8
82.0
81.4
82.0
81.4
200 FT
80.5
80
80.5
80.5
81
300 FT
78.5
78
77
76
77
78
79
79
78
77
76
400 FT
68
68
59
60
62
64
66
66
68
69
68
66
64
600 FT
56
58
56
52
48
50
54
56
57
54
56
52
54
800 FT

CONTOUR INTERVAL 0.2° F.

CONTOUR INTERVAL 0.5° F.

CONTOUR INTERVAL 1.0° F.

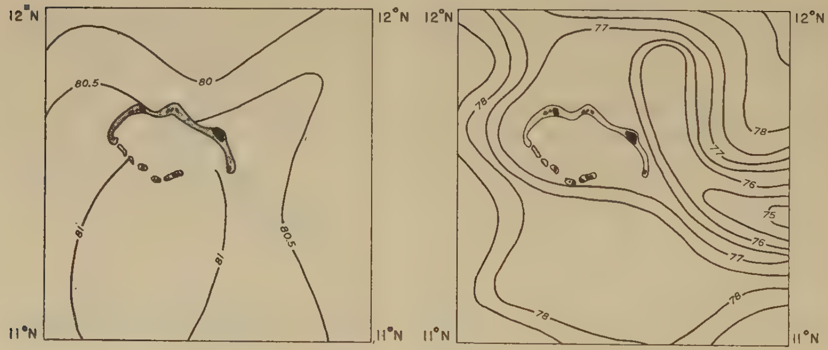
FIGURE 98.—Average temperature of water surrounding Bikini Atoll, May 8 to July 9, 1946, at the surface and at 200, 300, 400, 600, and 800 feet.


165°E
166°E
12°N
11°N
81
82
83
84
84.6
83.6
82.4
81.0
82.0
82.8

SURFACE

200 FT

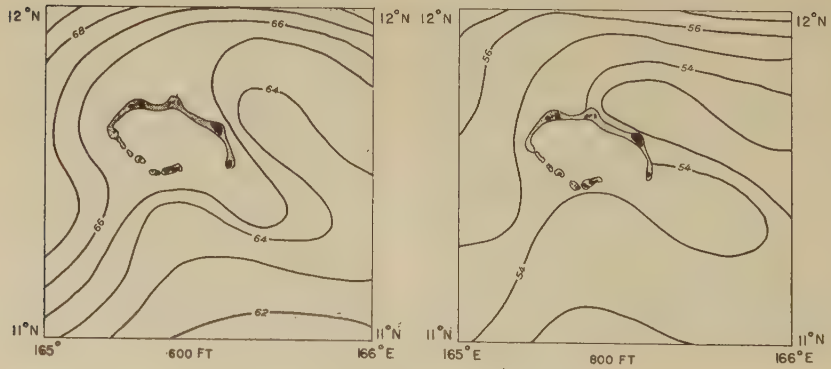
CONTOUR INTERVAL 0.2°F


12°N
11°N
80.5
80
81
77
78
76
75

300 FT

400 FT

CONTOUR INTERVAL 0.5°F.


12°N
11°N
165°
166°E
165°E
68
66
64
65
62
56
54

600 FT

800 FT

CONTOUR INTERVAL 1.0°F.

FIGURE 99.—Average temperature of water surrounding Bikini Atoll, July 20 to August 4, 1946, at the surface and at 200, 300, 400, 600, and 800 feet.

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Mao, Han-Lee, and Yoshida, Kozo, 1954, Physical oceanography in the Marshall Islands area: U. S. Geol. Survey Professional Paper 260–R.

Sverdrup, H. U., Johnson, M. W., and Fleming, R. H., 1946, The oceans, their physics, chemistry, and general biology, 1,087 p., 7 charts, New York, Prentice Hall, Inc.

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Plates 74, 75, 76, 77, 78, and 79 are in pocket at back of book

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STOCKHOLMS HÖGSKOLA

ON THE PHYLOGENY OF THE PYCNOGONIDA

BY

JOEL W. HEDGPETH
(Scripps Institution of Oceanography.*)

Essentia non sunt multiplicanda praeter necessitatem. William of Occam
... The only fact of cosmic significance in the whole subject of evolution in its broadest sense is the appearance of the single cell. A. H. Clark, *Zoogenesis,* p. 216.

CONTENTS.

1. The Classification of Fossil "Pantopoda" 193
2. On some Recent Flights of Phylogeny 203
Summary 211
References 211

1. THE CLASSIFICATION OF FOSSIL "PANTOPODA".

The pycnogonids are a group of curious marine arthropods of uncertain phylogenetic affiliations, remarkably uniform in certain basic structural characteristics. These are the "proboscis", a large, tripartite structure of one, or rarely two joints (when two jointed, the articulation is evidently a secondary modification), a reduced abdomen which is little more than a tubercle upon which the anus is situated, the absence of a well defined trunk or body, and legs composed of three short proximal or "coxal" joints, a long femur, two long tibial joints, a "tarsus and propodus" (actually a basitarsus and tarsus), in all, eight joints, and usually a large terminal claw, the dactylus or "transtarsus" of HANSEN. This is the extreme of reduction, found only in the females of a few genera; the males of these have en additional pair of appendages, the ovigers. The ovigers, actually the third pair of appendages, are present in both sexes of most forms.[1] The development of intratarsal muscles in the terminal segments of the ovigers is a feature not found in any other arthropods (SNODGRASS, 1952). Two other pairs of appendages are found in some families and genera, the chelifores (which may often be achelate in the adult and in some species are deciduous), and the palpi. Classification within

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* Contribution of the Scripps Institution of Oceanography New Series No. 701.

[1] The pycnogonids are usually characterized as having separate sexes; DUBOIS REYMOND MARCUS (1952) has described a hermaphroditic species, and it must be confessed that the great majority of species have not been too carefully examined, so hermaphroditism may be more widespread. Perhaps the curious business of transport and nursing of eggs by the male may have had its origin in a primitively hermaphroditic condition.

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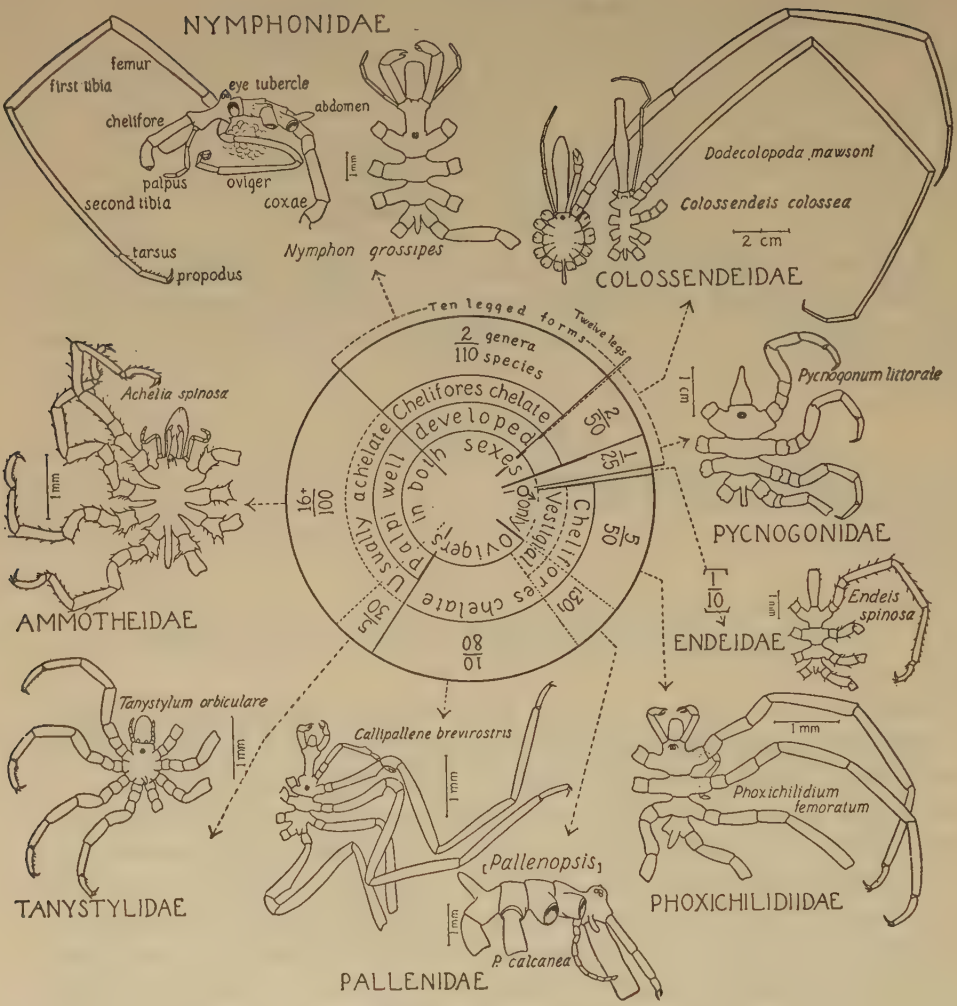
NYMPHONIDAE
femur
first tibia
eye tubercle
abdomen
chelifore
palpus
oviger
second tibia
coxae
tarsus
propodus
1 mm
Nymphon grossipes
Dodecolopoda mawsoni
Colossendeis colossea
2 cm
COLOSSENDEIDAE
Ten legged forms
Twelve legs
2 genera / 110 species
Chelifores chelate
developed
sexes
Palpi well
in both
Usually achelate
Ovigers
only ♂
Vestigial
Chelifores chelate
2/50
1/25
5/50
16+/100
5/30
10/80
1/30
1 cm
Pycnogonum littorale
PYCNOGONIDAE
1/10
1 mm
Endeis spinosa
ENDEIDAE
Achelia spinosa
1 mm
AMMOTHEIDAE
Tanystylum orbiculare
1 mm
TANYSTYLIDAE
Callipallene brevirostris
1 mm
Pallenopsis
1 mm
P. calcanea
PALLENIDAE
1 mm
Phoxichilidium femoratum
PHOXICHILIDIIDAE

Fig. 1. The families of Pycnogonida, showing the characters on which classification is based. (From Hedgpeth, 1947.)

the Pycnogonida is based primarily on the combinations of these three anterior pairs of appendages, and there are so many transitional forms that family divisions are not always clear and orders cannot be recognized (fig. 1).

The pycnogons (as many English zoologists call them) have no free swimming larval stage; in those forms for which the life cycle is known, the protonymphon larva (fig. 2), a curious six appendaged form reminiscent of the crustacean nauplius but more specialized than that larval form, works its way into a hydroid or other coelenterate, where it may form a gall, or into a mollusk or holothurian, and spends the early part of its life as a parasite, or at best a probably irritating commensal.

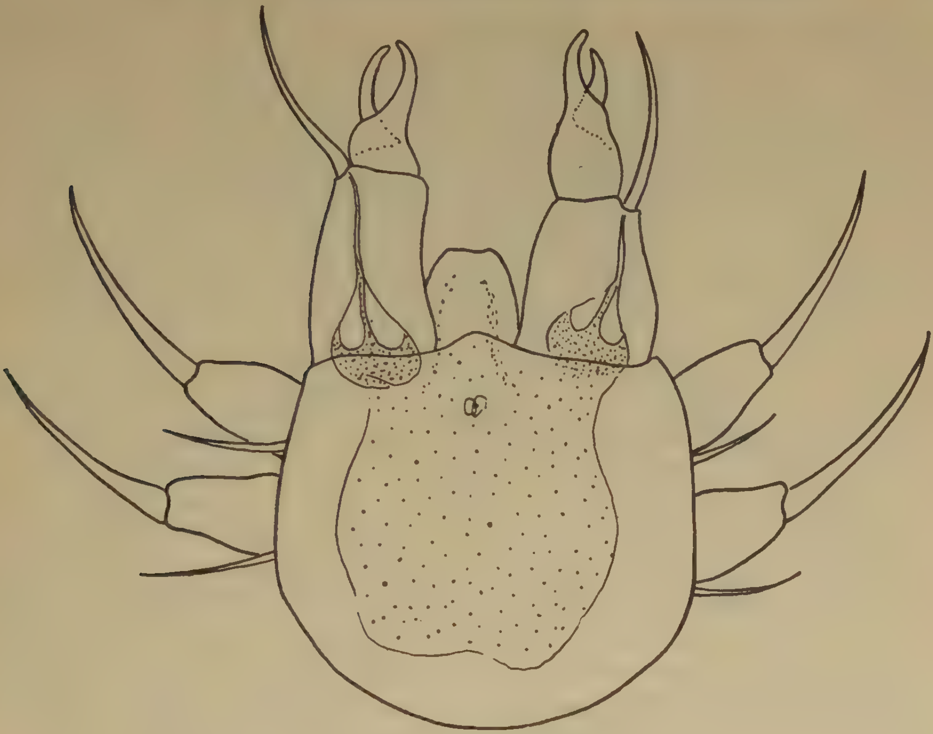

Fig. 2. A protonymphon larva.

If we examine the developing pycnogonid as well as the various types of adults, we find the following constellation of generalized characters:

1. The chelae are well developed, and comparatively large.
2. The palpi have at least 5 segments.
3. The ovigers are present in both sexes.
4. There are four pairs of walking legs, ending in a simple terminal claw or dactylus.
5. The proboscis is small, short and cylindrical, rather than long, pyriform or styliform.
6. There is no trace of an excretory system, but there is a secretory gland associated with the first appendage of the larva, and the male bears cement glands in the femoral segments of the legs.
7. There is no respiratory system.
8. In general, there are few spines, processes or tubercles on the legs and trunk, and prominent genital and cement gland tubercles are not developed.

These characters are essentially those of the family Nymphonidae, and to a lesser extent, of the Colossendeidae (disregarding the deciduous nature of the chelae in this family). At the other extreme we find the Ammotheidae, which, although possessing well developed palpi and, in some cases, chelate chelifores, exhibit the greatest development of spines, tubercles and processes. A curious and unique aspect of the Pycnogonida is the occurrence in certain families of extra trunk somites, bearing fully developed legs. Among the Nymphonidae there are at least two such ten-legged forms, and in the Colossendeidae there are several, together with one (*Dodecolopoda*), in which there are two extra somites. Such pentameric forms are also found among the Pycnogonidae, which show the extreme in reduction of anterior appendages in the group. As previously pointed out (HEDGPETH, 1947), the one aspect shared in common by these polymeric forms is a high ratio of species per genus in the families in which they occur, whereas in such families as the Ammotheidae and Pallenidae there are a large number of forms recognized as genera, with comparatively few species per genus. My suggestion that these polymerous forms may represent polymorphic species, perhaps induced by a polyploidic condition, still awaits more tangible evidence. If we regard them as examples of metameric instability, the question arises as to the possible body region in which this instability occurs. On the basis of the smaller second trunk somite and walking legs of *Pentacolossendeis* it was suggested that this instability occurred near the anterior end (HEDGPETH, 1947). This is similar to the suggestion that the intercalary rings of Notostraca are a result of a forward shifting of the growth axis (LINDER, 1945). A phenomenon of this character, associated with the production of appendages, as in the pycnogonids, might account for such apparently anomalous structures as the ovigers. Certainly the evidence for intercalary somites is stronger in the Pycnogonida than in any other group of arthropods.

In the past, the Pycnogonida (or Pantopoda, as they are called where Latreille's name is not conceded priority), have been most often classified somewhat vaguely with the Arachnida, or as an appendix to this class, or as a division of the Arachnoidea, an amorphous grab-bag of oddities perpetually offered to the innocent student in elementary textbooks and field manuals. Of late, the Pycnogonida have been considered to be of chelicerate stock, usually as a class of equal rank with the Arachnida and Xiphosura (to mention only the living), although they have such features as multiple genital openings and the oviger, which do not occur in the chelicerates.

Although often abundant, especially in colder seas, these animals, with their thin chitinous integument, are poor candidates for fossilization, and no fossils surely referable to the Pycnogonida, as characterized above, are known. Some years ago F. Broili described some strange arthropods from the Hunsrück shales of the Lower Devonian which he ascribed to the Pycnogonida, and although this has been received with reservation by active students of the living pycnogonids (CALMAN & GORDON, 1933; HEDGPETH, 1947; FAGE, 1949),

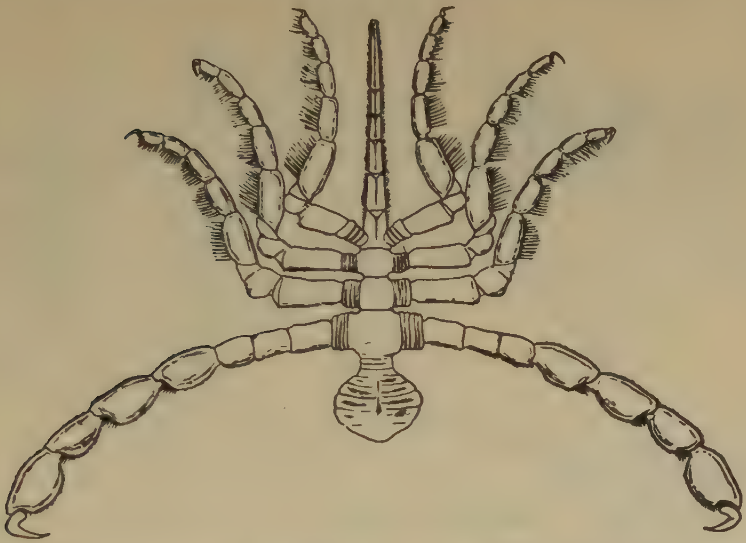

Fig. 3. The suggested restoration of *Palacoisopus problematicus* according to Broili (1933).

and somewhat less skeptically by MARCUS (1940), the attribution has been accepted without question by PETRUNKEVITCH (1952 a) and STØRMER (1944).

The fossil now known as *Palaeoisopus problematicus* was considered an isopod by BROILI (1928) when he first described it. A year later he described another find from the same formation, to which he gave the name *Palaeopantopus mauchcri* (BROILI, 1929). This fossil looks much more like a living pycnogonid than *Palacoisopus*, and was unhesitatingly referred to the Pantopoda, and on the occasion of describing another specimen a year later, BROILI (1930) set up the "group" Palaeopantopoda. Two years later BROILI (1932) decided that *Palacoisopus* was also a pycnogonid and in the following year (1933) published his final paper on this strange form, with palaeoecological inferences from the four known specimens. These inferences culminated in an imaginative drawing of *Palaeoisopus* swimming gracefully with its paddle like legs among a colony of stalked crinoids.

Palaeoisopus (fig. 3) was a large creature (about 20 cm span across the last pair of legs), with four pairs of appendages, the last pair paddle-like, a long anterior processes composed of perhaps five parts or segments, and a bulbous, apparently segmented, abdomen. The first three pairs of appendages are apparently 8-jointed, the last 7-jointed; all the legs terminate in hook-like claws. There is no well developed body, thus suggesting the usual form of a pycnogonid, and the cephalic segment seems to be the smallest. A most curious feature, which *Palaeisopus* shares with *Palaeopantopus*, is the formation of ring-like markings or structures on the lateral extensions of the body somites. These markings are apparent in only one leg of another nearly com-

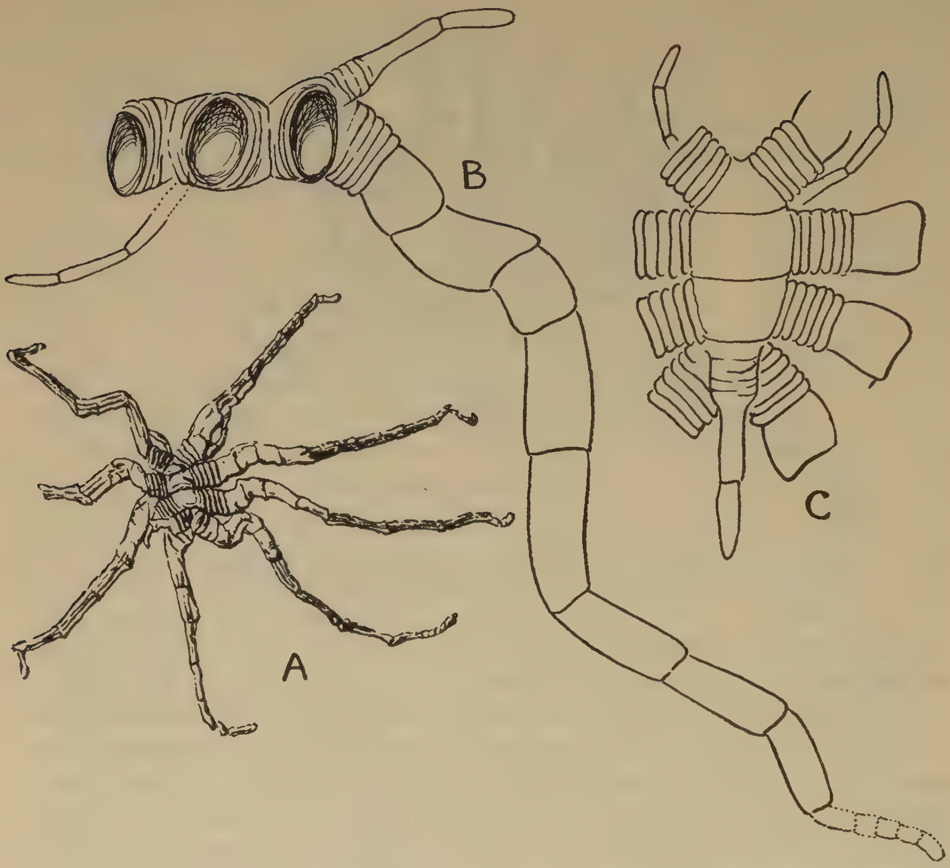

Fig. 4. *Palaeopantopus maucheri.* A, sketch of the fossil (from Broili, 1929). B., C., suggested reconstruction (original).

plete fossil (Broili, 1933). They are, however, very conspicuous in *Palaeopantopus.* At any rate, this ring-like structure is actually the only external feature, aside from the general reduction of the body to a pycnogonid-like aspect, that these two fossils share in common.

In *Palaeopantopus* (fig. 4), there seem to be at least 9 joints in the legs, with suggestions of small terminal joints reminiscent of an insect leg. In both the described specimens there is no trace of a proboscis, but there are suggestions of a 2- or 3- jointed abdomen and a pair of small anterior appendages whose position suggests ovigers although they look more like the palpi of existing pycnogonids.

Neither of these fossils resembles any other known fossil or recent arthropod very closely. There is a superficial resemblance between *Palaeoisopus* and the isopods of the genus *Pleurogonium* which have a bulbous pleotelson and rather well separated lateral processes, but the anterior part of *Pleurogonium* is

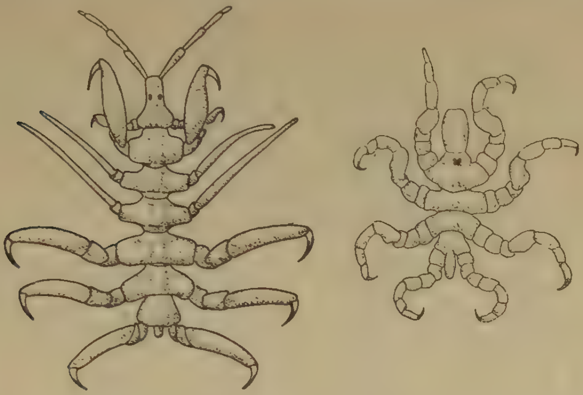

Fig. 5. *Paracyamus* and *Pycnogonum* (approximately same scale).

typically isopodan in appearance. The last pair of appendages of *Palaeoisopus* resemble the enlarged peraeopods of *Munnopsis*, another specialized isopod. These are only coincidental resemblances, somewhat like the superficial similarities between the whale-louse *Cyamus* and *Pycnogonum*, which caused some confusion in Linnaean times, Linnaeus in fact called the common shore pycnogonid of Europe *Pycnogonum balaenarum*, evidently under the impression that *Cyamus* and *Pycnogonum* were the same thing (fig. 5). Such superficial resemblances reach fantastic extremes in insects and spiders, but have little if any bearing on phylogenetic relationships.

This strange *Palaeoisopus* is a fascinating object, with its jointed anterior process and bulbous posterior. Broili discerned no less than five segments in this proboscis, the second of which he counted as the first trunk segment. If we are to accept this interpretation, the last pair of legs falls in the ninth somite, in agreement with the serial homologies of Carpenter, Wirén and Henry (Table 1). This, of course, does not prove anything, and confronts us with the difficulty of homologizing several apparently cylindrical somites with those bearing the chelifores, palpi, and ovigers of the living pycnogonids. If we are to take this at face value, this anterior nozzle-like structure of this Lower Devonian fossil represents a high degree of specialization.[2] The posterior end of the fossil poses some more difficulties: as Petrunkevitch (1952 b) has pointed out, the loss of abdominal segments is one of the most important evolutionary trends in the Arthropoda. In the living Pycnogonida this reduction has reached an end point: the abdomen is nothing more than a tubercle with a distal anus, although in a few species in may be rather long

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[2] While it is true, as Hansen (1930, p. 107) says, that "a segment of the body in an Arthropod is in its simplest form a ring chitinized on all sides", the examples he gives are of posterior segments; an anterior segment should also have a pair of appendages or at least a basic sensory structure. To be an Arthropod at all, the appendage would have to consist of at least two segments with an intervening joint. (See Pryor, 1951, for a theory of the origin of jointed appendages from tubular processes.)

Tab. 1. *A Half-century of homologies.*

	CARPENTER, 1905			WIRÉN, 1918			FAGE, 1949			FERRIS & HENRY, 1949—53		
Somite	Pyc.	Xiph.	Arach.	Pyc.	Xiph.	Arach.	Pyc.	Xiph.	Arach.	Pyc.	Xiph.	Arach.
		M O U T H			*M O U T H*						*M O U T H*	
1	eyes	eyes	eyes	dorsal antimere	rostrum	rostrum	Chelifores & dorsal antimere	Chelicera	Chelicera & labrum	proboscis	rostrum	labrum
								M O U T H				
2	—	—	rostrum	chelifores	chelicera	chelicera	palpi & ventral antimeres (*ovigers*)*	1st leg	pedipalps	base of proboscis	base of rostrum	[absent]
3	chelifores	chelicera	chelicera	"pedipalp" & ventral antimeres	pedipalps	pedipalps	1st leg	2nd leg	1st leg	chelifores	outer carapace	chelicera
4	palpi	—	—*	palpi	1st leg	1st leg	2nd leg	3rd leg	2nd leg	palpi	pedipalps	pedipalps
5	ovigers	1st leg	pedipalps	oviger	2nd leg	2nd leg	3rd leg	4th leg	3rd leg	ovigers	2nd leg	1st leg
6	1st leg	2nd leg	1st leg	1st leg	3rd leg	3rd leg	4th leg	5th leg	4th leg	1st leg	3rd leg	2nd leg
7	2nd leg	3rd leg	2nd leg	2nd leg	4th leg	4th leg	abdomen	pregenital	[pregenital]	2nd leg	4th leg	3rd leg
8	3rd leg	4th leg	3rd leg	3rd leg	abd. 1	abd. 1		genital	genital	3rd leg	5th leg	4th leg
9	4th leg	5th leg	4th leg	4th leg	genital	genital				4th leg		
10	abdomen	pregenital	[pregenital]	abdomen						abdomen		
11		genital	genital									

*(*non-homologous*)

*Vestigial in *Epeira*
[Items in brackets refer to condition in the scorpion]

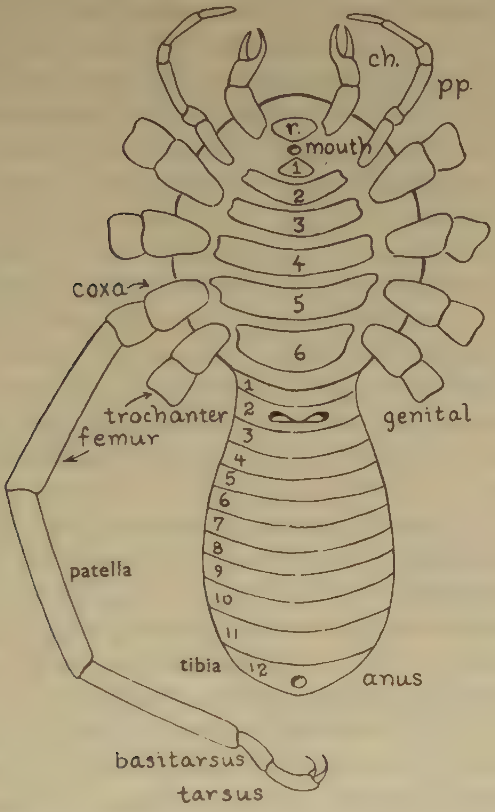

Fig. 6. Hypothetical generalized arachnid, ventral aspect. (original, with the assistance of A. Petrunkevitch).

and spinose. The large abdomen of *Palaeoisopus* is evidently connected to the trunk by a constriction, suggesting again a specialized condition, which if the animal belongs to the chelicerate stock at all, would seem to set it off on a divergent line from the basic arachnid type (fig. 6). A large abdomen suggests the retention of the gonads in the structure, so we cannot say that the Pycnogonida are derived from *Palaeoisopus* by simply pinching off the abdomen at the constriction without somehow getting the gonads through it into the thorax or prosoma, which seems unlikely. In *Limulus,* in which the gonads have anterior branches into the prosoma, the abdomen is broadly joined to the prosoma; if the Pycnogonida have stemmed from some chelicerate stock it is more reasonable to suppose that the gonads have attained their present anterior position by migrating through a similarly broad connection between the abdomen and the prosoma.

In those chelicerates which have been studied in detail, the germ primordia appear very early in development, although the position of the genital openings is remarkably constant (on the second abdominal segment). It is difficult to see how new genital openings could be developed on all the body somites in response to a forward migration of the gonad from the abdomen. However, the possibility of early development of the gonads in the Pycnogonida might have been associated with an inhibition of the original posterior migration. That is, the gonads might have matured before their migration into the posterior part of the body could take place.[3]

It is possible that the ventral groove suggested in the abdomen by BROILI in his reconstructed *Palaeoisopus* is the genital orifice; if so, it seems to be well back of the second abdominal somite, which PETRUNKEVITCH (1949) considers one of the few good reference points in the anatomy of fossil arachnids. On the basis of the available evidence, therefore, we cannot even place *Palaeoisopus* near the Chelicerata, and if anything is plain about this fossil, it is that it lacks the two pairs of antennae and biramous appendages, so it cannot be a crustacean. All that we can say of it is that *Palaeoisopus* is an Arthropod, *incertae sedis*.

Disposition of the other fossil, *Palaeopantopus,* is not so simple; indeed, there is no valid evidence for excluding it from the modern Pycnogonida although certain essential features are lacking or not apparent. Two specimens have been described, in neither of which is there a suggestion of a proboscis, but in both specimens we can see only the dorsal surface, and the possibility that the creature may have had some sort of proboscideal structure recurved and carried ventrally cannot be dismissed. The absence of eyes and of various anterior appendages means nothing as many living pycnogonids lack these structures. The apparently two or three segmented abdomen cannot be regarded as a character incompatible with the range of variation observed in the existing pycnogonids, as there are some with two pairs of abdominal ganglia. The segmented abdomen might be cited as evidence in support of the suggestion that the gonads migrated into the prosoma early in the history of the group as the abdomen was gradually reduced from the posteriormost somites, narrowed down to little more than a jointed tube. Since PETRUNKEVITCH (1949) has presented evidence that the major chelicerate groups completed their differentiation by Devonian times, the appearance of a pycnogonid-like animal in the Lower Devonian, already well separated from any chelicerate stock, can be accepted with equanimity.

The most logical, although not necessarily natural, disposition of this fossil is to recognize it as the representative of an order, the Palaeopantopoda (BROILI, 1930), and to consider all the existing pycnogonids as belonging to an equivalent category, for which we may use Pantopoda (GERSTAECKER, 1863), retaining Pycnogonida (LATREILLE, 1810) for the class or subphylum as a whole. Efforts to fit the Pycnogonida into any schemes with the arachnids or chelicerates should be abandoned, and the meaningless term Arachnoidea should be forgotten. By accepting *Palaeopantopus* as a pycnogonid, we have to recognize that the trend toward reduction of the arthropod abdomen was completed by Devonian times in this peculiar group, and hence the Pycnogonida may be among the oldest of living groups of arthropods.[4]

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[3] An interesting analogy is the absorption of the germ primordia in Comatulids and the development of the definitive gonad in the axial organ (MORTENSEN, 1920, pp. 68—69). This reminds us, incidentally, that Austin Clark once published a paper titled "The Echinoderms as Aberrant Arthropods" (Smiths. Misc. Colls., vol. 72 no. 11, 1921).

2. ON SOME RECENT FLIGHTS OF PHYLOGENY.

The amiable pastime of phylogenetic arboriculture seems to be back in favor these days, if indeed it had ever fallen out. The literature of the last fifty years is especially rich in such speculative exercizes, and the Pycnogonida have been one of the favorite subjects of what HANSEN (1925) called "that cheap and easy-going occupation." Probably HANSEN'S stern contempt deterred many from venturing into phylogeny, and there have been few serious attempts to place the pycnogonids into a phylogenetic scheme, with formal tables of homologies, since the effort of WIRÉN (1918). At the turn of the century LANKESTER (1904) laid down the law and the prophets, uncritically dumping the Pycnogonia, as the sub-class Pantopoda, into his grade Nomoneristica of the Arachnida, along with *Limulus* and all the rest, with three orders.[5] CARPENTER (1905) also considered the Pycnogonida to be arachnids, and attempted to determine homologies throughout the Arthropoda. He managed to fit the Pycnogonida into his scheme by deciding that that all other arachnids lacked a head segment, the fourth or palpus-bearing somite of the Pycnogonida. WIRÉN (1918) studied the nervous system of several pycnogonids in some detail and endeavored to establish homologies with other arthropods which are somewhat more logical than CARPENTER'S; unlike CARPENTER, he made a serious effort to solve the problem of the proboscis. His suggestion that the latero-ventral antimeres represented the pedipalp somite and that the vestiges of these structures were represented by the teeth at the tip of the proboscis has not been seriously entertained by students of the Pycnogonida. This idea, based in part on faulty observation, was criticized by HANSTRÖM (1919), who denied the segmental nature of the proboscis. The problem of the proboscis has recently been attacked (*inter alia*) by HENRY (1953), again from the viewpoint of the nervous system. She concludes that "it is composed of elements of the first and second body segments; thus it is homologous to the labrum and clypeus of the Crustacea and the Insecta and the rostrum of *Limulus*, and the proboscis of the Polychaeta."

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[4] This contradicts my earlier view (1947) that the Pycnogonida are a relatively new group of arthropods; at that time I had not seriously considered Broili's fossils.

[5] These orders are Nymphonomorpha, Ascorhynchomorpha and Pycnogonomorpha. FAGE (1949) follow's Bouvier's system of four orders, including Cole's Colossendeomorpha. D'Arcy Thompson, in the Cambridge Natural History (1909) seems to have been the first to abandon the attempt to segregate the Pycnogonida into discrete orders, at least in a reference text.

It would seem that HENRY considers the pycnogonid proboscis *directly* homologous to the polychaete proboscis, in brief, little more than an everted and stiffened polychaete proboscis: "It appears that it can be directly homologized with the proboscis of the polychaete worms, which is similar in form. We [i.e., HENRY & G. F. FERRIS] suggest that the sclerotized teeth within the apex of the proboscis are homologous to the teeth or jaws of the polychaetes." HENRY also suggests that the peculiar eye tubercle of the pycnogonid is "homologous with the ocular portion of the prostomium of the polychaete worms." When we add to these statements their observation that the Pycnogonida "to some extent" share the polychaete trait of lacking a fixed number of body segments, it is obvious that FERRIS and HENRY are prepared to place the Pycnogonida closer than any other arthropods to the polychaetes. This is, of course, an idea that has been entertained by other speculative zoologists as far back as DOHRN (1881): "Die Pycnogoniden-Organisation ziegt zwar wenig direkte Beziehungen auch zu Anneliden, aber wenn wir sie in frühere Zustände aufzulösen versuchen, werden wir schliesslich wohl noch zunächst auf Annelidenähnliche Bildungen stossen."

If we are to consider the pycnogonid and the polychaete proboscis homologous, how are we to explain the fact that one is composed of three longitudinal antimeres and the other is made of two ring-like parts? To be sure, HENRY states only that the jaws of the polychaetes and the denticles of the pycnogonid proboscis are "directly homologous." But it is also considered (HENRY, 1947) that the polychaete proboscis is actually composed of three segments, the first represented by the jaws, the second by the oral ring and the third by the maxillary ring (fig. 7). Yet she finds that the pycnogonid proboscis "is composed of elements of segment one and segment two" (HENRY, 1953, p. 19); segment two, however, is not an integral part of the pycnogonid proboscis but is only "the base . . . which bears the insertion of the muscles which move the proboscis." This seems a rather tenuous extension of the concept of homology; it does not follow that similar structures performing essentially the same function are *ipso facto* homologous. If they are homologous, and the primary indication of such homology resides in the topographic arrangement of the nerves (one of the guiding principles of the FERRIS—HENRY school), where is the polychaete homologue of the median rostral nerve of the pycnogonid? And how do we derive the trefoil arrangement of teeth in the pycnogonid from the paired jaws of the polychaete? To be sound homology, there should be point for point correspondence of the parts involved (cf. REMANE, 1952, ch. 2); this cannot be demonstrated for the proboscides of pycnogonid and polychaete.

We hesitate to beg the question by suggesting that the pycnogonid proboscis

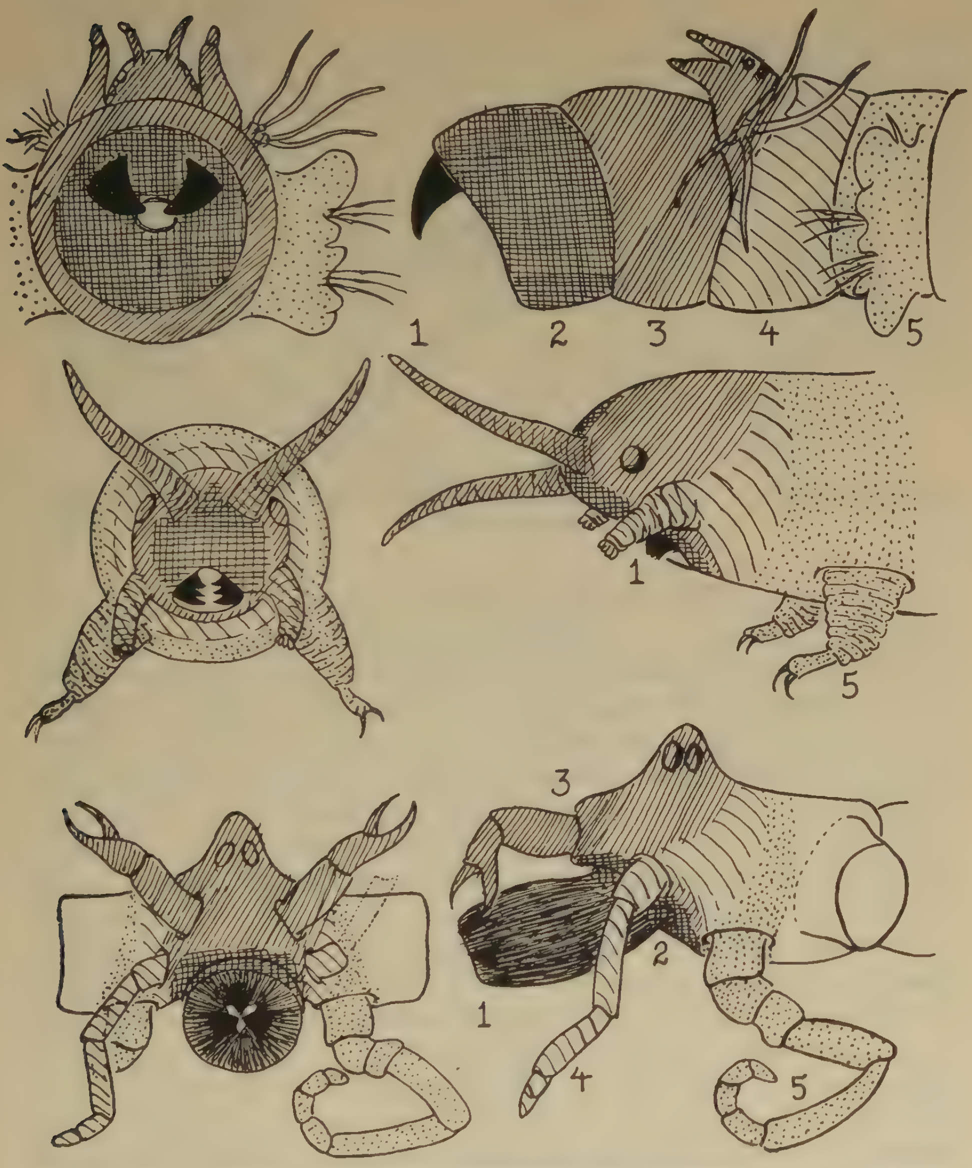

Fig. 7. Anterior ends of a polychaete, onychophoran and pycnogonid, with the segmental homologies according to Ferris and Henry.

may be a secondary structure, without counterpart in any living arthropod (although it bears some superficial resemblance to the sucking apparatus of a tick). Certainly the anterior ganglia and nerve ring are features adapted to meet the need of this instrument, if one may be permitted such a teleological expression. The composite origin of the proboscis is indicated by the origin

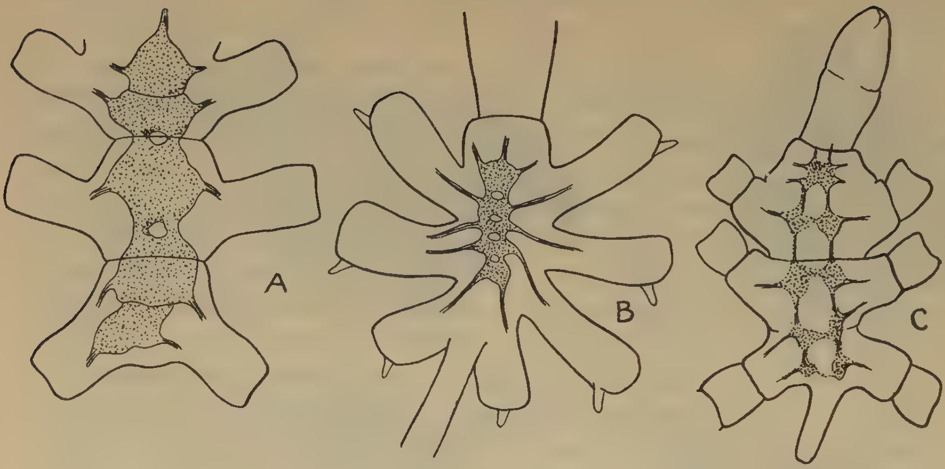

Fig. 8. Distribution of main nerve trunks in various abnormal pycnogonids (From Hedgpeth, 1947).

of the nerves that serve it, although Henry would have it that the median rostral nerve and the nerves of the lateral antimeres all originate primitively from the stomodeal ganglion. In such genera as *Colossendeis* and *Ascorhynchus* in which the proboscis is more anterior than ventral in position, the rostral nerve arises well toward the median anterior surface of the protocerebrum, while in *Nymphon* and *Anoplodactylus,* which carry the proboscis more ventrally, the origin of this nerve is nearer the base of the protocerebrum, according to Henry's drawings. Since the Pycnogonida, like the Arachnida, lack the deutocerebrum, Henry suggests that the rostral nerve has been carried forward from the tritocerebrum, where it properly belongs since it innervates the stomodeal system, and all stomodeal nerves must come from the tritocerebrum according to her theory. If this is so, why do we not find the rostral nerve much nearer the tritocerebrum in those forms in which the probscis is more ventral than anterior in its position? Can it be that the now-missing deutocerebrum is represented by the anterior ganglia of the proboscis? The conclusions arrived at by Henry depend in large part on the hypothesis that the nerves of a segmental ganglion do not innervate any organs but those which they originally served in the primitive condition. It is perhaps unfair to cite abnormalities, but the anomolous ditribution of the main nerve trunks in some freak specimens (fig. 8) suggests that this hypothesis must be applied with caution in the case of the pycnogonids.

As for the polychaete proboscis, it may well represent the everted stomodeaum rather than a pre-oral structure, as Ferris and Henry propose, but that does not mean that we need to consider that it is composed of remnants of primary somites. A suggestive bit of evidence is found in the larval devel-

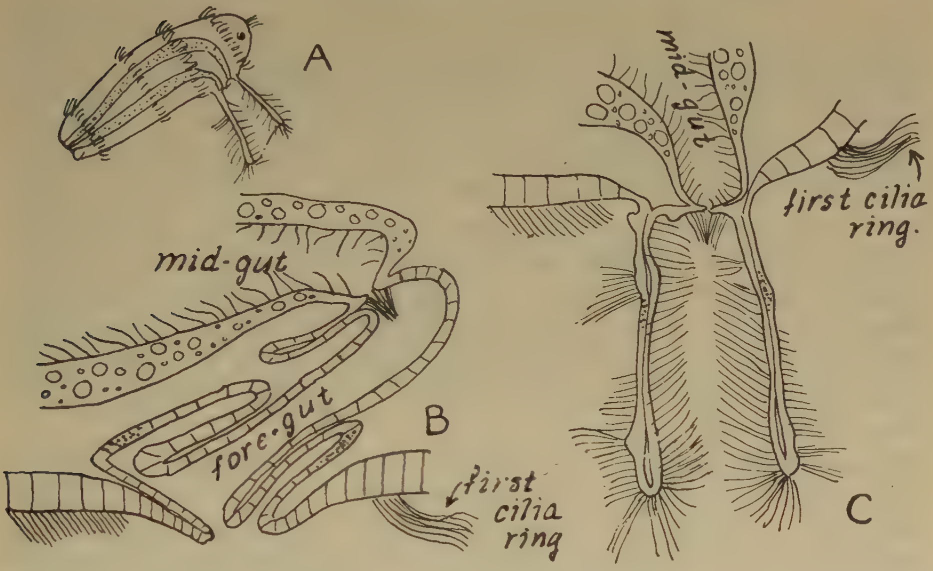

Fig. 9. The larval "proboscis" of *Protodrilus*. A. View of larva; B. proboscis retracted; C. expanded. (After Jägersten.)

opment of the archiannelid *Protodrilus* as described by JÄGERSTEN (1952): "... the larvae of Protodrilus have the foregut evertible in the form of a funnel during the growth period. In other words, this part of the gut is developed into an apparatus of a highly specialized nature for catching microplankton. This is an unmistakable adaptation to the pelagic life." This larval "proboscis" (fig. 9), which is lost in the process of metamorphosis, is apparently a modified stomodeal structure rather than a derivative of primary somites. Such a structure as this lends credence to the suspicion that the polychaete proboscis may be a paedomorphic structure, or certainly acquired after the establishment of primary segmentation. Perhaps the parasitic mode of life of larval pycnogonids led to the formation of a somewhat similar proboscis well after the divergence from the basic articulate (or annulate) stock?[6]

As is well known in phylogenetic circles, FERRIS and his student HENRY have been busy for the last several years trying to establish a new concept of the segmentation of the arthropod head, based primarily on studies of the topographic arrangement of the nervous system in selected annelids and arthropods. According to what might be considered the classical theory of arthropod segmentation, the head consists of a "prostomium" (the remnant of the acron or top of the trochophore), and several (usually 3) pre-oral somites; the mouth may be considered initially the anterior—most structure and to have migrated backward to its present position on the third somite before the evolution of the somites as we know them. FERRIS compares this Lankesterian hypothesis of "adaptational shifting" of the mouth to a "belief in witchcraft" (1950, p. 127), and maintains that there are no true pre-oral somites or a prostomium, that the mouth has attained its present somewhat posterior position by differential growth of the anterior body somites or by their posterior ventral flexure. He contends that the present arrangement of the cephalic ganglia is secondary, that their true origin is indicated by the topographic arrangement of the nerves in the adult example. The conclusions concerning the nature of the insect head which have been reached by this approach are beyond the province of this discussion; the most judicious critique seems to be that by DUPORTE (1953).

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[6] The temptation to add a leaf to GARSTANG'S posthumous volume (1951) is irresistible:

The pycnogonid leads a parasitic youth,
and never grows a large abdomen;
A precocious polychaete perhaps,
of arthropods a paedomorphic omen.

Whether deliberate or not, an elaborate scheme of phylogeny imposes interpretations not necessarily in accord with the available facts, and many phylogenies have collapsed from internal stresses. The famous Limulus-theory of PATTEN (1912), which still has its admirers, is the most spectacular example.[7] Since the aim of phylogeny is to propose a plausible explanation for the incomplete record before us, we should not try to bridge the gaps in the present record (to say nothing of the past) with spans whose engineering is basically unsound. The usual device for this is Occam's Razor, which is not an engineering tool but a logical device that cuts as deeply or as superficially as its wielder thinks necessary.[8] It is a rather large assumption to make, that the procession of events in nature coincides with our notions of what is orderly and logical. Perhaps it was some concern over this aspect that caused SNODGRASS to recant: "The head characters of the arthropods will be seen to be so variously distributed in the several arthropod groups that they cannot be made to fit consistently into any theoretical scheme of arthropod interrelationships, and the writer hereby retracts whatever views on the subject he may formerly have expressed." (1951, p. 5.)[9]

The usual refuge from such difficulties is to put things at bit farther off by saying the group involved is polyphyletic, that is, it represents the result of several different lines of descent converging to an apparently similar type. Many perhaps most—phylogenists consider this philosophically untenable, a multiplication of explanations beyond the necessary minimum, comparable, so to speak, "with a belief that nature must then have been playing some pretty tricks in convergent evolution of an inconceivable magnitude" (Heslop-Harrison, 1952). At the other extreme we have such efforts as that of Patten to derive the vertebrates from Limulus, or the still unfulfilled promise by Raw (1949) to trace the Arthropoda from a particular family of still-living polychaetes.[10]

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[7] GREGORY (1950) regards Patten's book with "profound respect" but nevertheless denies its principal thesis.

[8] FERRIS, especially in his general statements (1948, 1950, 1953), invokes this instrument frequently, yet resorts to less defensible philosophical methods in replying to some of his critics. E.g. "No such nerve appears in our material. No such nerve should be present. If the generalizations previously offered are valid no such nerve can be present." (1953, p. 12.) This may be good debating technique, but it sounds like dialectical materialism on paper although Ferris denies such taint.

[9] While I have fond personal regards for Dr. SNODGRASS, I cannot but wonder what H. J. Hansen would have said about this roosting of his "phylogenetic eagle."

While Ferris and Henry do not go to the extreme suggested by Raw, a large part of their theorizing is based on the assumption that the parent arthropod stock is similar to the polychaetes *as at present constituted:* "If we assume that that the other groups of the Annulata have actually evolved from ancestors having the same general structure as do the Polychaetes . . ." (Henry, 1947, p. 94). Even when phylogeny is restricted to the anterior end of the animals, this assumption leads to difficulties, as we have already seen, and much of the argument over whether the mouth shifted backward or the head grew forward seems beside the point in view of the general agreement that the mouth is primitively the anteriormost structure of an elongate, bilateral predecessor to both Annelids and arthropods.[11] One hesitates to remind Ferris and Henry that the backward movement of the mouth is plain in many embryos (cf. especially Manton, 1949), since they have little faith in such observations: "It might be thought that embryology will give us the answer to our problems, but we have the simple fact that embryology has not done so." (Ferris, 1953, p. 4). Nevertheless, embryological evidence is resorted to by Henry in support of her view that the median rostral nerve of the pycnogonids originated in the tritocerebrum. In any event what is known of the embryology of arthropods and onychophorans indicates that there has been a long period of specialization and larval modification in these groups and that it has proceeded in quite a different direction from that of the polychaetes. While there may be superficial resemblances between the front end of a pycnogonid and a polychaete, the posterior end would seem to have more in common with an arachnid or perhaps the onychophorans. The embryology of the pycnogonids is in some ways more suggestive of the Crustacea than of the Arachnida, but the primary appendages appear after the proboscis although the proboscis originates

[10] Raw, p. 20, writes: "... we can hypothecate for the primitive annelid" but does not mention what he proposes to mortgage for this worm.

[11] If the trochophore larva bears any resemblance at all to the progenitor of the articulate (or annulate) line, the latero-ventral position of the mouth must be viewed as evidence that the "adaptational shift" or "dorsal growth" was a very early development, occurring before the origin of either of the great trochophore lines. the articulate and vermiform branch and the molluscan branch. Of course, a discussion of "pre-oral somites" in the unsegmented mollusca would be even more abstractly academic than many of the arguments about the position of the mouth in a segmented animal, but theories concerning the position of the mouth as related to dorsal ganglia should apply equally to both groups. If, however, we adopt the radiate-acoel hypothesis (Cf. Hyman, The Invertebrates, vol. 2 1951, pp. 5—10) of the origin of a bilateral animal from a solid radial organism with a ventral (or "posterior") mouth, we have to say that the mouth was never anterior to the principal ganglionic mass.

fairly well back on the ventral surface of the adult pycnogonid. This is a bit of a puzzle if we assume that the proboscis is a primitive structure, homologous to the polychaete proboscis. Ferris and Henry would say that it is obvious that the post-oral somites have grown dorsally and anteriorly, leaving the base of the proboscis on the ventral surface. This would be acceptable if the proboscis were a comparatively simple structure, but it is not. In both structure and origin it differs from the polychaete proboscis, and its early appearance in the embryo would seem to be a late specialisation, probably related to the development of a specialized larval stage. Could it be that the Devonian *Palaeopantopus* had simply a ventral mouth and that it was gradually produced forward, thus forming a proboscis? Or has a larval structure similar to that of *Protodrilus* been carried on to the adult? In some protonymphons the dorsal lobe of the proboscis bears a chitinized point—the "arrowhead"—which is a specialized structure for piercing the theca of the hydroid parasitized by the larvae. Was the proboscis originally a piercing structure derived from mouth parts, or is this "arrowhead" a new development?

More difficulties are encountered if the somites posterior to the head region are considered. Probably Ferris and Henry did not intend to imply that the stenopod appendage of the pycnogonid is a direct descendant of the polychaete parapodium, although this seems implicit in their scheme of homology. They may well be homonymous, but their differences suggest again that we are dealing divergent lines, and attempts to homologize these structures have not been succesful.

The so-called cement glands of the pycnogonids pose another puzzle. These glands occur on the femurs of the males, and suggest segmental organs derived from primitive excretory organs. A similar pair of glands occurs on the first appendage of the larvae, reminiscent of the cement gland of the Cypris larva of barnacles. Are these cement glands homologous to the slime and crural glands of onychophorans? They seem to be more like the onychophoran structures than the composite coxal glands of arachnids with which they have sometimes been compared.

It is obvious that the plausibility of an elaborate phylogeny is inversely proportional to the number and ontogeny of the organ systems used in constructing the phylogeny. Certainly the sum of morphological and developmental features in the Pycnogonida indicates that they cannot be affiliated with any other arthropod group as at present constituted although one restricted scheme of phylogeny might place them directly on the polychaete stem and another might just as confidently place them near the roots of the Onychophora, and their general aspect has long suggested that they are some sort of arachnids, or at least chelicerates. What little paleontological evidence is available indicates, as Marcus (1940, p. 119) says, "que os antecessores paleozoicos dos Pantopoda actuaes eram Pantopoda e não Crustacea, ou Arachnomorpha." Whatever we may wish to speculate about their origin, we certainly cannot disagree with SNODGRASS (1952, p. 56): "It is impossible to arrive at any positive conclusion concerning the relationships of the Pycnogonida, except that they are Arthropods."

SUMMARY

1. The Pycnogonida cannot be included in the Chelicerata or Arachnida; the term Arachnoidea, an unnatural waste basket category, must be abandoned, and the Pycnogonida should be recognized as an independent arthropod branch. The *Pycnogonida* may be divided in two orders, Pantopoda for the living forms, and Palaeopantopoda for the Devonian fossil *Palaeopantopus*.
2. One of the weakest links in the speculations of the Ferris—Henry school is their assumption that the polychaetes resemble the parent stock of the arthropods. Both must be considered survivors of long evolutionary processes.
3. There is some suggestion that intercalary somites, near the anterior end but posterior to the head may occur in the Pycnogonida but it cannot be said whether this is the result of instability in growth or abnormal chromosome number.
4. It is possible that the polychaete proboscis is a paedomorphic structure; the pycnogonid proboscis may have developed after the divergence of the Pycnogonida as an independent group and the two structures cannot be homologized.

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Plankton of Northern Marshall Islands

By MARTIN W. JOHNSON

Bikini and Nearby Atolls, Marshall Islands

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CONTENTS

Page
Abstract 301
Introduction 301
Methods of collecting 301

Bikini Lagoon:

Concentration of plankton fauna 302
Capacity of the lagoon to foster an endemic fauna 303
Maintenance and concentration of oceanic plankton in the lagoon 305

Bikini Lagoon—Continued

Inflow and discharge of water from the lagoon as indicated by the drift of planktonic life 306
Other lagoons of the northern Marshall Islands 307
Phytoplankton 309
Literature cited 314

ILLUSTRATIONS

Page
FIGURE 101. Positions of plankton hauls taken at Bikini Atoll 302
102. Distribution of *Undinula vulgaris*, by stations 303
103. Diurnal migration of *Undinula vulgaris* 304
104. Diurnal migration of ostracodes 304
105. Diurnal migration of zooplankton 304
106. Distribution of *Tretomphalus planus*, by stations 305
107. Distribution of *Globerigina*, by areas 306
108. Distribution of copepods, by areas 307
109. Distribution of *Appendicularia*, by areas 308
110. Distribution of the pteropod, *Creseis* sp., by areas 309
111. Distribution of arrow worms, *Sagitta* spp. by areas 310
112. Distribution of crab larvae, by areas 311
113. Distribution of shrimp larvae, by areas 312
114. Distribution of fish eggs, by areas 313
115. Distribution of fish larvae, by areas 314

TABLE

TABLE 1. Relative number per cubic meter of certain plankton organisms in four lagoons in the northern Marshall Islands 308

PLANKTON OF NORTHERN MARSHALL ISLANDS

MARTIN W. JOHNSON[1]

ABSTRACT

Most of the holoplankton species found in Bikini Lagoon occur also in the surrounding open sea. The plankton fauna of the lagoon, however, is characterized by (1) a number of endemic species not found outside the lagoon except where washed out by outflowing currents, and (2) a concentration within the lagoon of many forms that occur normally also in the outside surface waters. Both features are dependent upon the degree of dispersal of the plankton and are therefore directly correlated with the semiclosed circulation which the lagoon imposes upon the water that flows in over the eastern and northeastern reefs.

A study of the vertical distribution and diurnal vertical migration of the endemic copepod *Undinula vulgaris*, and of the general plankton, reveals that much of the lagoon plankton lives mainly n the deeper, slowly (0.1 knot) eastward-moving counter current which as a water mass represents 70 to 90 percent of the living space in the lagoon. Even during the night when much of the plankton migrates toward the surface into the faster (0.3 knot) westward-moving water, about two-thirds of the plankton still remains within the deeper counter current.

Much of the oceanic plankton swept into the lagoon thrives there and becomes concentrated so that the average concentration per cubic meter of water of the 11 most common animal groups is about four times higher than in the outside northeastern area, and twice higher than the outside western-southern area of principal outflow. The increased concentration found in the outside water to the west and south indicates an outwash from the lagoon in that area and is shown especially by such forms as *Undinula vulgaris* and *Tretomphalus planus* (foraminifer), which occur abundantly in the lagoon but were not found in the area mmediately to the east and north of the atoll.

The restricted water flow within the lagoon is biologically mportant in conserving also the transitory planktonic larval stages of lagoon and reef fishes and bottom-living animals.

A comparison of the plankton in Bikini, Eniwetok, Rongerik, and Rongelap Lagoons showed the last to be the richest for the period of the survey. Phytoplankton was exceedingly sparse n all but Rongelap, where a small "bloom" was in progress.

INTRODUCTION

By the term "plankton" is meant all the organisms, usually microscopic or semimicroscopic, that float about n the sea with little or no resistance to water currents. Thus, in general, they are dispersed and transported n a manner dependent upon the prevailing current system. The animal plankton consists not only of such forms as are permanently planktonic all of their lives (holoplanktonic), but also of the transitory young or larval stages of bottom-living forms—such as crabs, certain shrimp, clams, and others—and fishes.

In an earlier report (Johnson, 1949) the plankton was studied with a view to its use in corroborating the physical oceanographic findings relative to the water exchange between Bikini Lagoon and the surrounding sea.

From a biologist's standpoint, however, the greatest significance of the study involves an evaluation of the ecological effect of the water currents in the maintenance of a consistently endemic or concentrated population within the lagoon and on the wave-washed reefs that form its banks.

Bikini Lagoon rests as a marine lake on the summit of a coral-capped volcanic mountain which rises abruptly from the floor of the open ocean at a depth of more than 2,000 fathoms. The lagoon has a maximum depth of about 35 fathoms (Emery, Tracey, and Ladd, 1949). At low tide it is completely isolated from the sea except for a number of passages forming gaps 6 to 35 fathoms deep in the reef along the southern and southwestern periphery. (See fig. 101.) Depending upon tidal action and wind conditions, the waters of this "lake" are partially renewed daily by a flow of water over the reefs from the sparsely populated surrounding high seas.

METHODS OF COLLECTING

The quantitative plankton samples were taken in two ways in each of four lagoons:

1. Horizontal tows were made with Clark-Bumpus samplers, which give a measure of the volume of water filtered through the net. The nets used with these samplers were of No. 2 bolting silk having apertures of about 0.366 millimeter.

Inside the lagoons, two samplers were usually towed 20 to 30 minutes simultaneously at 1- and 10-fathom depths. Deeper horizontal towing within the lagoon was hazardous because of the many coral pinnacles rising from the bottom. For the 24-hour series in Bikini Lagoon, 3 samplers were towed in series at depths of 1, 10, and 25 fathoms over a course previously surveyed to assure an absence of shallower coral obstructions. Outside the

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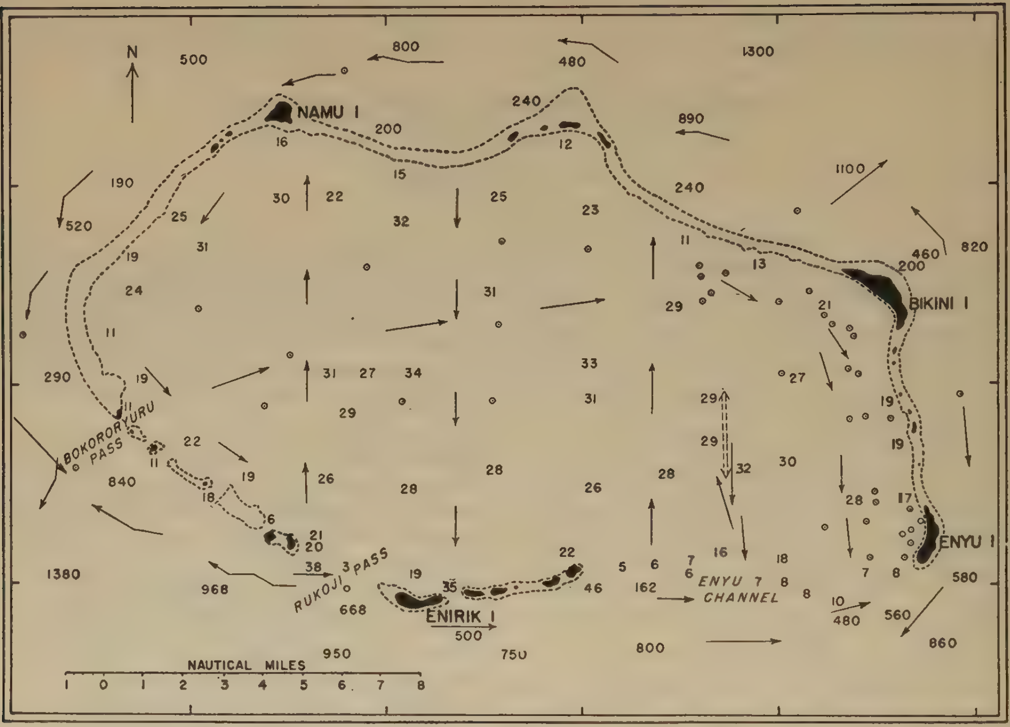
N
NAMU I
BIKINI I
ENYU I
ENIRIK I
BOKORORYURU PASS
RUKOJI PASS
ENYU CHANNEL
500
800
480
1300
240
890
200
16
12
1100
190
520
25
30
22
15
32
25
23
240
31
19
24
11
460
200
820
290
19
31
27
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1380
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668
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7
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8
10
480
560
7
8
580
500
950
750
800
860
NAUTICAL MILES
1 0 1 2 3 4 5 6 7 8

Figure 101.—Positions of plankton hauls taken at Bikini Atoll March 10 to May 18, 1946; the arrows indicate course of horizontal hauls; the circles indicate vertical hauls; the figures are depths in fathoms.

lagoon the samplers were towed simultaneously at 1-, 10-, and 40-fathom depths. The station positions and courses over which the Bikini samples were taken are shown in figure 101.

2. Vertical tows were made with a 10-inch net of No. 20 bolting silk having apertures of 0.076 millimeter. These nets were pulled up vertically from a depth of 50 meters or, where depths were shallower, from the bottom to the surface. The water filtered in the regular hauls was about 2.5 cubic meters. The purpose of obtaining this series was to sample the more minute organisms of the phytoplankton together with the tintinnids, copepod larvae, and clam larvae that pass through the coarser nets.

The following numbers of stations were occupied for quantitative hauls in each of the four lagoons: Bikini, 81; Eniwetok, 18; Rongelap, 35; Rongerik, 11. The No. 20 net was used at about 50 percent of the stations in each lagoon.

The regular quantitative hauls were checked qualitatively by many irregular hauls with various types of nets. A total of 437 tows are involved in the whole survey.

BIKINI LAGOON

CONCENTRATION OF PLANKTON FAUNA

Insofar as Bikini Atoll is concerned, this report deals mainly with observations made between March 10 and May 18, 1946, before the atomic-bomb tests. A few samples (not shown in fig. 101) taken outside the lagoon as late as August 8, 1946, and contrasted with the spring samples, showed no appreciable change in concentration in the plankton.

Perhaps 90 percent or more of the holoplanktonic forms found in Bikini Lagoon occur also in the outside surrounding water. The lagoon plankton fauna is, however, characterized by the following two striking features: (1) A number of the important species are endemic to the lagoon and are seldom or never found outside except at localities where they have been washed out of the lagoon over the reef or through passages; (2) there is a concentration of many forms that also occur normally in the outside surface water. In eneral, the plankton concentration in the Marshall slands area is relatively sparse, especially the phytolankton.

APACITY OF THE LAGOON TO FOSTER AN ENDEMIC FAUNA

The capacity of the lagoon to foster an endemic fauna nd to concentrate the fauna common to the lagoon nd the outside water results largely from the same echanism. This mechanism is inherent in the current attern which results mainly from the retarding effect hat the lagoon has on the oceanic water which it intercepts from the North Equatorial Current. This type f dependence on water currents is doubtless characterstic of other lagoons similarly constructed.

In some areas, such as the Gulf of Maine, for example, he endemic population is correlated with a large circular low of water which produces a semiclosed system Bigelow, 1924; Redfield, 1941). In Bikini Lagoon the urrent mechanism is much smaller and operates mainly n a vertical rather than horizontal plane.

Surface water in the lagoon is driven by the prevailing trade winds in a west-southwest direction, whereas the water at intermediate and greater depths flows in the opposite direction as a counter current. This gives rise to sinking in the western portion of the lagoon and to upwelling against the eastern reefs (Von Arx, 1948).

In the search for endemic species in Bikini Lagoon, the most useful thus far considered are *Undinula vulgaris* (Dana), a copepod crustacean, and *Tretomphalus planus* Cushman, a pelagic foraminifer. This foraminifer was identified by the late J. A. Cushman, who described the species originally from Samoa and stated that it occurs also in Fiji. Both species occur also in the lagoons of Eniwetok, Rongelap, and Rongerik.

Undinula vulgaris.—This is a widely distributed species which, though reported from the open ocean, appears to be preponderantly a lagoon form in this area. Large (more than 2 millimeters) and easily recognized, it occurs in varying numbers throughout most of the lagoon. During the period March 10 to

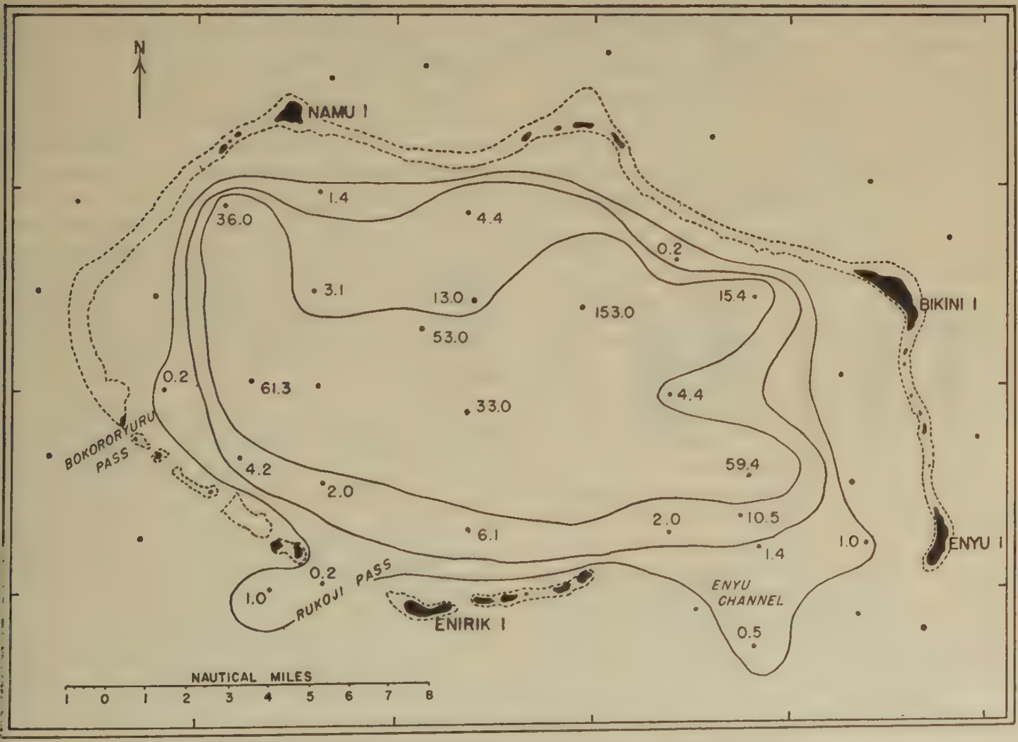

FIGURE 102.—Number of *Undinula vulgaris* per cubic meter of water, by stations (black dots).

May 18 it was present at about 90 percent of the lagoon stations. The largest numbers (as many as 255 per cubic meter of water) have been taken near the center of the lagoon. (See fig. 102.) In the daytime the animals seek the deeper water strata, 10 fathoms or more deep. Very few specimens were caught in the net towed at or above the 1-fathom depth except at night. It is obvious that to maintain an endemic population of an animal with a relatively long life history like that of *Undinula vulgaris*, and in such numerical concentrations, there must be a pattern of currents which leads to a relatively closed system with very slow flushing of at least a large part of the lagoon. This would require the presence of a sizable counter current or some other effective retarding system. The hydrographic study has indicated that a deep slowly moving countercurrent exists. Thus the biological and hydrographic observations support each other on this point.

During the time the animals are in the upper surface layer near the outwash of the lagoon, they are in danger of being swept out through passages or over the reef. Therefore, reproduction in the deeper layer would have to be at a rate sufficient to replenish the loss of numbers washed away by the surface layer, or where there is slow reproduction the bulk of the population would have to spend the greater part of the time in the deep, slowly moving countercurrent. That the latter occurs in Bikini Lagoon is indicated by a study of the diurnal vertical migratory journeys of *Undinula vulgaris* and a number of other planktonic forms. (See figs. 103, 104, and 105.) It will be seen from the illustrations that not only *Undinula* but the bulk of the other planktonic forms avoid the more lighted surface waters during the day and that a goodly portion (two-thirds or more) of the population remains even at night in the slowly moving (average 0.1 knot) countercurrent. This current involves 70 to 90 percent of the water mass of the lagoon—that is, 70 to 90 percent of the living space. Nevertheless, at night much of the population must be transported towards the western and southern margins of the lagoon by the relatively fast-moving (average 0.3 knot) surface current. Depending upon wind velocity, the depth of this current varies from 2.5 to 10 fathoms, with an average of 6.5 fathoms (the maximum depth of the lagoon is about 35 fathoms). At the approach of dawn a downward movement of the animals occurs, and a slow journey eastward begins. In this manner about one-third of the distance lost during the night is recovered during the day. It is probable that this is the order of events with many larval forms of bottom-living adults in the lagoon and also with the oceanic forms swept into the lagoon over the eastern reefs. Biologically this is very important in conserving not only the holoplankton but also the transitory larvae that eventually settle to the bottom of the lagoon or on the reefs to restock the bottom-living animals.

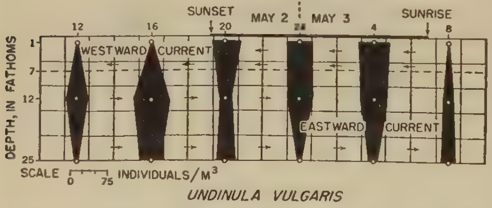

FIGURE 103.—Diurnal migration of *Undinula vulgaris;* 35-minute horizontal hauls taken at surface and at 10 and 25 fathoms at 4-hour intervals over course shown by double dashed arrow in figure 101.

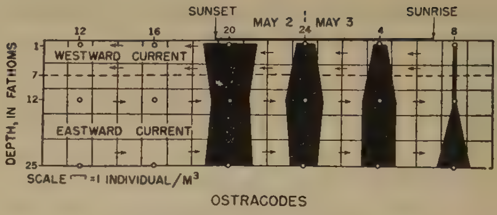

FIGURE 104.—Diurnal migration of ostracodes.

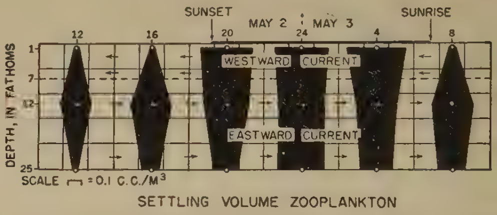

FIGURE 105.—Diurnal migration of total zooplankton as represented by settling volume.

Tretomphalus planus.—This species was found in all parts of the lagoon, sometimes in numbers up to 175 individuals or more per cubic meter of water. The average was, however, only about 25 per cubic meter. This species was present throughout the whole period of investigation (Mar. 10 to Aug. 8) and occurred at all depths within the lagoon. The greatest concentrations were in the upper 10 fathoms except in a few instances where numbers were greater in the deeper strata.

The plankton samples collected outside the lagoon yielded this species only at stations along the western and southern periphery of the atoll. The greatest outside concentrations were found near the passages, thus suggesting the main route of outwash for the species as indicated in figure 106. Apparently small

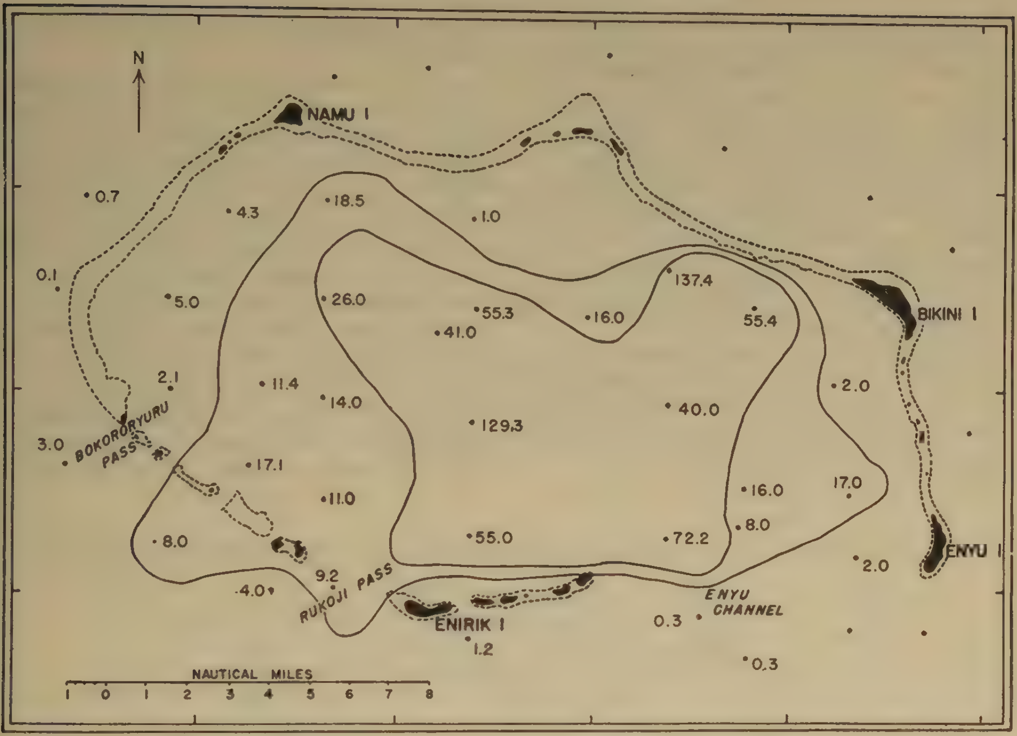

FIGURE 106.—*Tretomphalus planus*, number per cubic meter of surface water by stations (black dots).

umbers are washed out also over the long shallow reef xtending from Bokororyuru Pass to Namu island. his is in keeping with the animal's habit of floating ear the surface. The deeper-living lagoon animals, uch as *Undinula vulgaris*, are discharged through the assages (depths varying from 6 to 35 fathoms) rather han over the reef.

From the above observations it appears that *Tre-* *omphalus* is endemic to the lagoon, perhaps requiring hallow water during the early stages of its life history efore the float chamber has been developed. This ould explain its absence or scarcity in deep water utside the lagoon except where washed out on the own-current side by the prevailing flow through the goon. It should be pointed out here that this relaonship suggests the use of *Tretomphalus* as an index past oceanographic conditions of the atoll. Provided s tests are well preserved as fossils in the sediments, it ould serve to show the general direction of currents at have swept through the lagoon in past history, for ough the animal is kept suspended by the float chamber while alive, there must be a gradual precipitation of defunct tests to the bottom along the course of the outflowing water.

MAINTENANCE AND CONCENTRATION OF OCEANIC PLANKTON IN THE LAGOON

The salinity and temperature of the water within the lagoon differ but little from that outside. The highest lagoon salinity (34.85 parts per thousand) is only about 0.1 part per thousand higher than in the open ocean, and the temperature change from about 27.02 C to 27.10 C is negligible. The vertical gradients of these factors are also insignificant. In these respects the lagoon water is essentially oceanic and would therefore not be seriously inimical to most of the surface oceanic plankton coming in over the reef.

The concentration of oceanic plankton that has drifted into the lagoon results from the semiclosed circulatory pattern in the lagoon. Presumably this circulation would operate in a mechanical manner similar to its effect on the maintenance of the endemic fauna. In the following section it will be shown that certain forms that are common to the inside and outside may be as much as 27 times more numerous per unit of water inside the lagoon. This increased concentration doubtless results in part from better food conditions inside as a result of local production, but the reduction of dispersal must be very important.

The presence in the lagoon of many egg-bearing specimens and a large proportion of larval and juvenile stages of species common to the outside is evidence of successful reproduction inside. In the absence of wide and uninterrupted dispersal, such as occurs outside, a concentration from both reproduction inside and recruitment from outside should occur.

In summarizing the average concentration by areas of the 11 most common animal groups, it appears that the ratios of concentration per cubic meter for (*a*) the outside eastern-northern area, (*b*) the inside lagoon area, and (*c*) the outside western-southern area of principal outflow, are roughly a:b:c:=1:4:2.

INFLOW AND DISCHARGE OF WATER FROM THE LAGOON AS INDICATED BY THE DRIFT OF PLANKTONIC LIFE

When we compare the number of specific organisms occurring per cubic meter of water at stations occupied inside the lagoon with the number found in the surrounding water just outside the reefs and passages, it is seen that the concentration is almost invariably smallest in the waters outside the eastern and northern reefs. It is nearly always largest by far at the stations within the lagoon, and intermediate at stations just outside the western and southern passages and reefs. The largest outside catches occur near Rukoji Pass and the western portion of Enyu Channel (figs. 102, and 106 to 115). Figures 102 and 106 are especially useful since they deal with two endemic species and show clearly the route by which the species are washed out of the lagoon. According to hydrographic studies, the outflow is through these passages and over these reefs, and this is clearly corroborated by the biological evi-

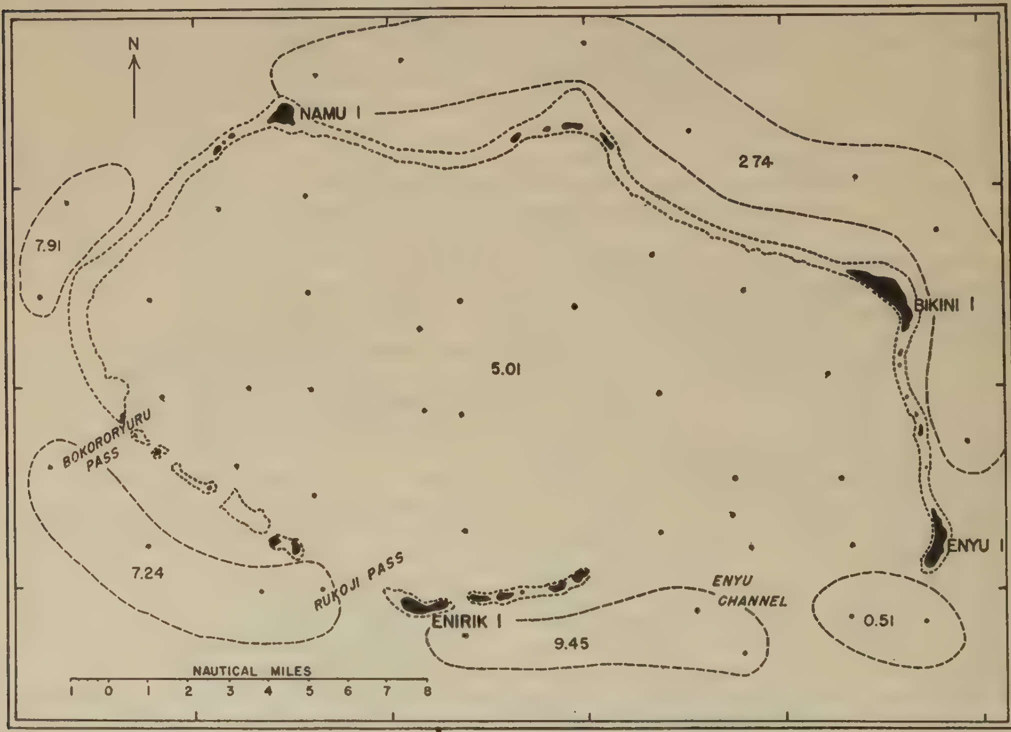

FIGURE 107.—*Globigerina*, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

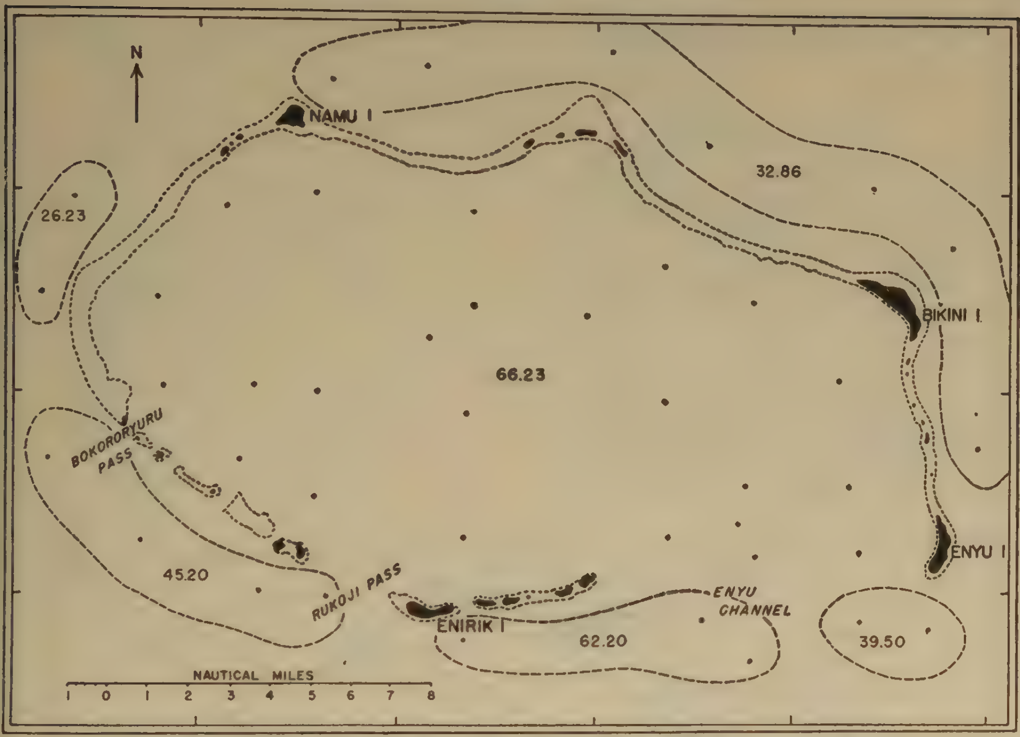

FIGURE 108.—Copepods, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

lence. The biological evidence does, however, indi- ate a somewhat broader outwash from Enyu Channel n the early part of the survey than the hydrographic harts indicate.

From the hydrographic survey we learn that in the pen sea off Bikini Atoll there is a small northward radient in temperature and salinity so that the water ntering the lagoon from the north is about 0.1 degree C) colder and 0.3 part per thousand more saline than hat which enters the southern passes.

The plankton has not yet been studied in sufficient etail to know the extent of its usefulness in indicating ther than the general routes of entry into the lagoon. he distribution of one copepod species, *Copilia irabilis*, does, however, suggest that its center of stribution may be in the southern water with which enters the lagoon through Enyu Channel and over e reef between Bikini and Enyu islands. Forty-four percent of the stations in the southern half of the lagoon yielded this species; only 11 percent in the northern half. Outside the lagoon from near Bikini island around the southern periphery of the atoll to near Arriikan Pass on the west side, 75 percent of the stations yielded the species. None was taken at outside stations north of these points. Nowhere was the species found in abundance.

OTHER LAGOONS OF THE NORTHERN MARSHALL ISLANDS

Plankton surveys were made in the lagoons of Eniwetok, Rongelap, and Rongerik Atolls for comparison with Bikini Lagoon. Table 1 gives the result in type and average concentration of the more important organisms for the periods indicated.

The first part of table 1 is based on collections with the Clark-Bumpus samplers with No. 2 mesh net, the

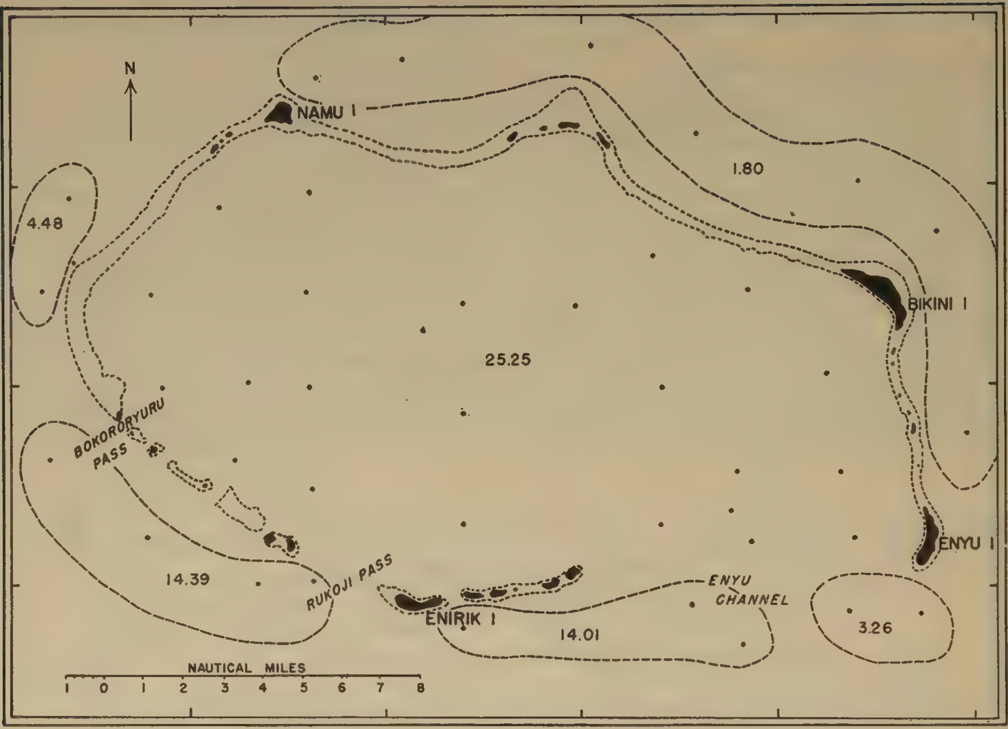

FIGURE 109.—*Appendicularia*, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

TABLE 1.—*Relative number per cubic meter of certain planktonic organisms in four lagoons of atolls in the northern Marshall Islands*

Where density could not be determined, mere presence of an organism is indicated by a plus sign (+)]

	Bikini (March 25—May 18)		Eniwetok (June 2–14) Inside lagoon	Rongelap (June 18–22) Inside lagoon	Rongerik (June 23–24) Inside lagoon
	Inside lagoon	Outside lagoon			
Collected with Clark-Bumpus samplers—No. 2 mesh net					
Globigerina	5.01	5.56	0.41	10.88	0.62
Tretomphalus planus	25.15	1.3	2.30	6.64	3.07
Acartia hamata	5.05	51.2	8.46	3.93	4.60
Corycaeus spp	15.89		.68	16.44	3.04
Oithona spp	3.31		.38	6.17	2.31
Undinula vulgaris	18.51		4.11	(+)	1.94
Microcalanids	19.59		1.88	22.66	3.95
Crab larvae	3.31	.82	5.92	5.05	2.44
Shrimp larvae	4.41	1.08	5.06	13.84	4.78
Echinopluteus	(+)	(+)	.75	139.1	(+)
Ophiopluteus	(+)	(+)	2.30	3.50	(+)
Creseis (pteropod)	11.30	.95	.36	.34	.02
Chaetognaths	7.47	1.83	5.67	5.76	4.03
Appendicularia	25.25	7.6	1.76	26.18	47.62
Fish eggs	1.45	.66	.09	2.27	.73
Fish larvae	.61	.16	1.15	3.64	1.43
Collected with No. 20 mesh net in hauls from 50 meters to surface					
Tintinnids	95	76	271	326	309
Copepod larvae	551	298	555	1,065	483
Clam larvae	334	6	41	1,091	774
Diatoms	435	85	905	534,345	734
Dinoflagellates	1,137	273	595	1,572	631

second part on 50–0 meter hauls with the No. 20 mesh net. The amount of water filtered by the No. 20 net is subject to some error because of the drift of the ship, but this was not usually too serious since the hauls were so shallow. The numbers given for the No. 2 net hauls are doubtless minimal for some groups with small members because of the selective size of the mesh. This is especially true for the small copepods *Acartia*, *Corycaeus*, *Oithona* and for some less common cyclopoids.

On the basis of these surveys some important differences come to light relative to the standing crop within the lagoons. It is seen that Rongelap and Bikin Lagoons appear to have a somewhat richer planktonic fauna than do the other lagoons, especially Eniwetok This was noticeable especially for the copepods as a group. For these the numbers per cubic meter of water with the No. 2 net were: Bikini, 62.37; Rongelap 57.17; Rongerik, 18.08; and Eniwetok 15.74.

Pending further taxonomic analysis of the collection it will be useful to list the following holoplanktoni species as being among the more common for th lagoons:

Copepoda:

Acartia hamata Mori.
Calanus pauper (average 4.62 per cubic meter in Bikini Lagoon).
Calanopia minor (very common in Rongelap Lagoon).
Calocalanus pavo.
Candacia spp.
Centropages elongatus.
  sp.
Clausocalanus pungens.
Copilia mirabilis.
Corycaeus spp.
Eucalanus attenuates.
Labidocera sp.
Lubbockia squillimana.
Oithona plumifera.
Oncea venusta.
Sapphirina stellata.
Scolecithrix danae.
  sp.
Tortanus murrayi.
  gracilis.
Undinula darwini (found outside only).
  vulgaris.

The list of Copepoda is far from complete for the whole area and for the rarer species.

Chaetognaths:
  Sagitta enflata.
    robusta.
    serratodentata.

The siphonophores occurring in the samples have been discussed by Sears (1950).

One conspicuous difference in the zooplankton of the lagoons was the relatively large number of different larval forms, including fish, in Rongelap Lagoon. Specific identification could not be made of the larvae; most of the shrimp larvae were snapping shrimp.

PHYTOPLANKTON

Another notable difference pertains to the phytoplankton caught with the No. 20 net. The standing crop of phytoplankton was exceedingly small in most of the lagoons, and this was verified by the blue color and great transparency of the water. In Rongelap Lagoon,

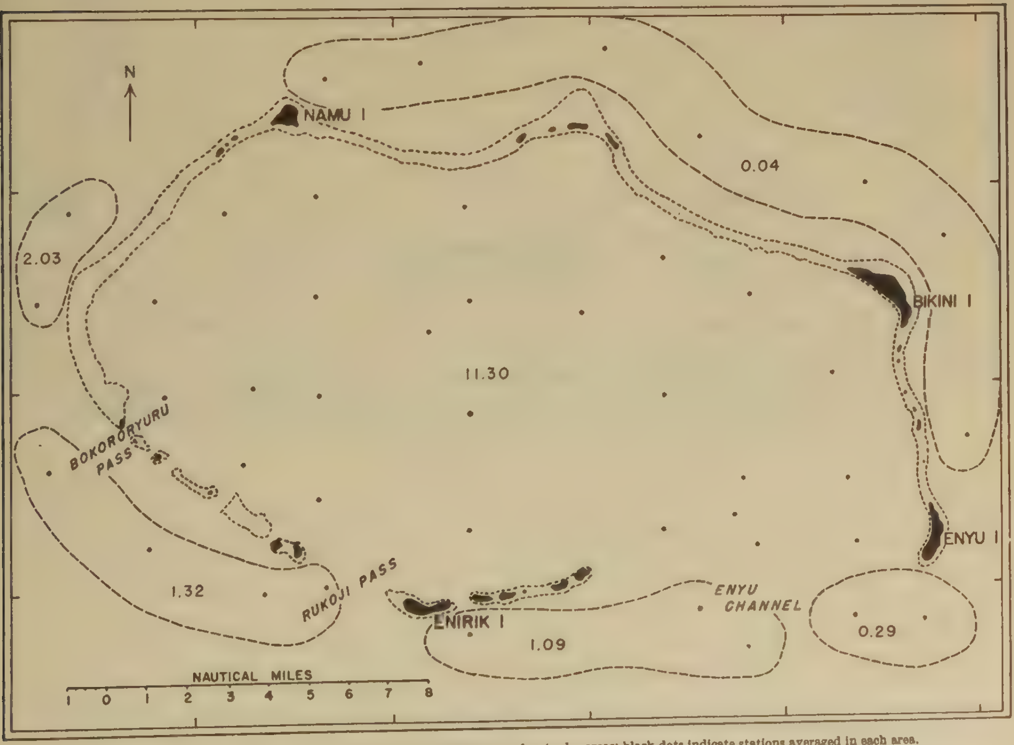

FIGURE 110.—Pteropod, *Creseis* sp., average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

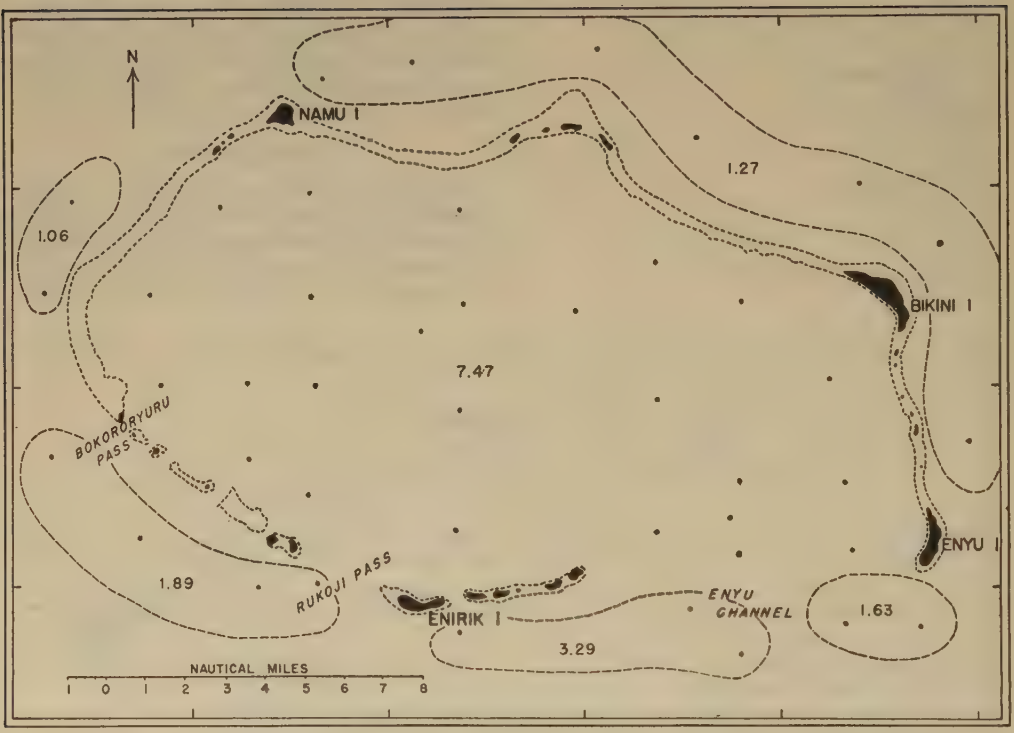
N
NAMU I
1.27
1.06
BIKINI I
7.47
BOKORORYURU PASS
ENYU I
1.89
RUKOJI PASS
ENYU CHANNEL
1.63
ENIRIK I
3.29
NAUTICAL MILES
1 0 1 2 3 4 5 6 7 8

FIGURE 111.—Arrow worms, *Sagitta* spp., average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

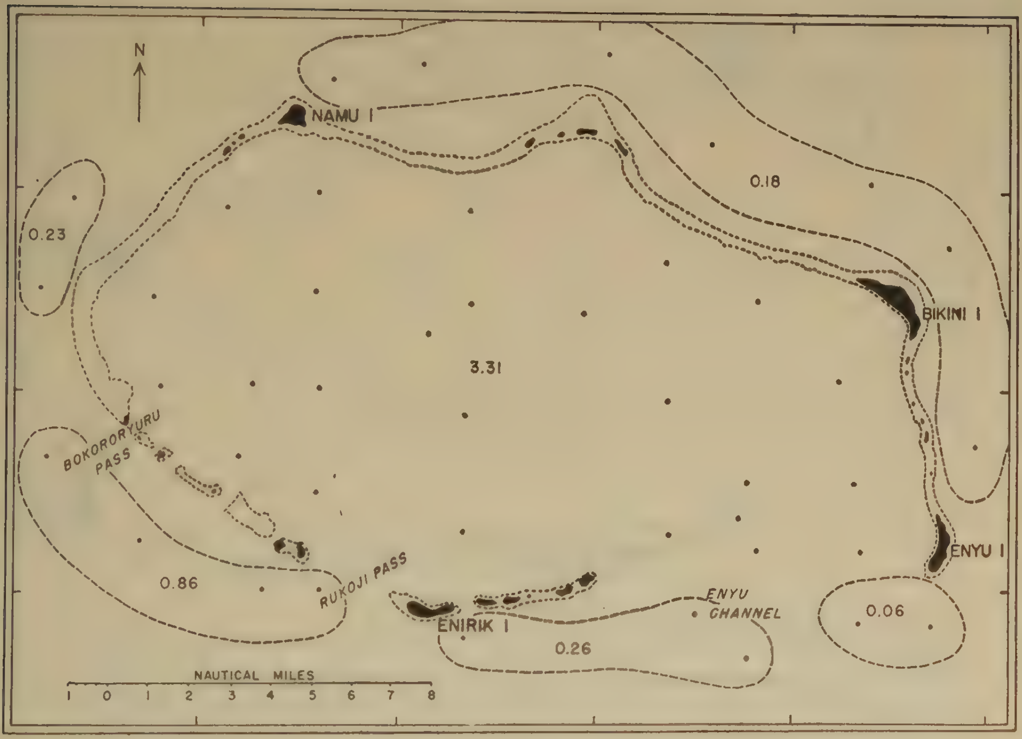
N
NAMU I
0.23
0.18
BIKINI I
3.31
BOKORORYURU PASS
RUKOJI PASS
0.86
ENIRIK I
ENYU CHANNEL
0.26
ENYU I
0.06
NAUTICAL MILES
1 0 1 2 3 4 5 6 7 8

FIGURE 112.—Crab larvae, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

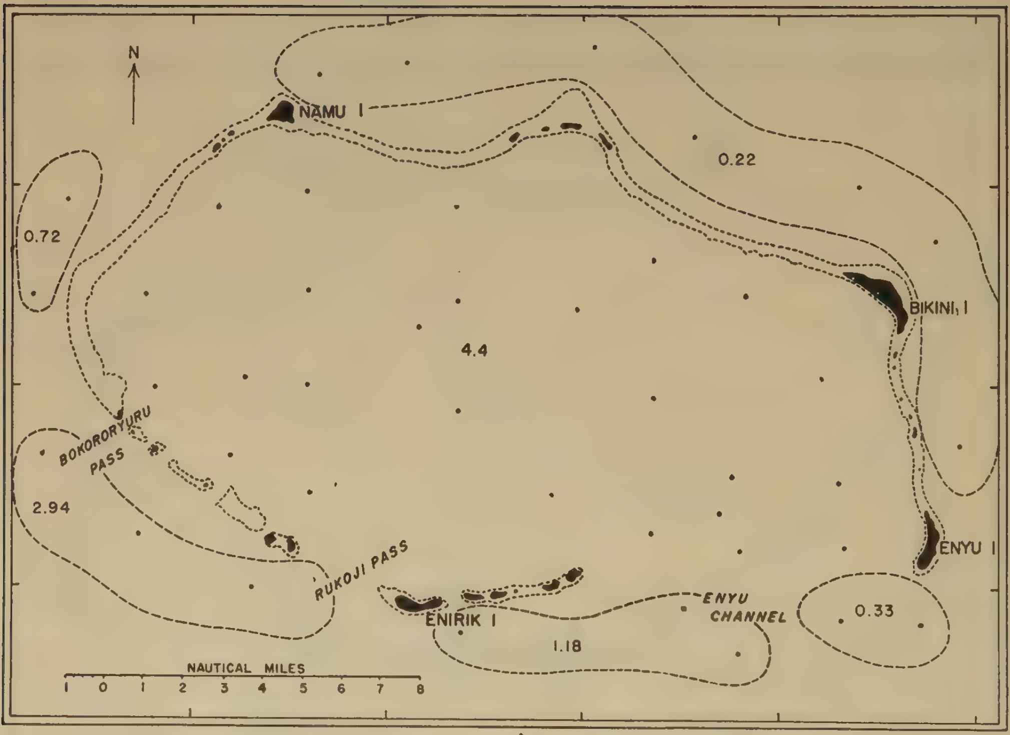
N
NAMU I
0.22
0.72
4.4
BIKINI I
BOKORORYURU PASS
2.94
RUKOJI PASS
ENYU I
ENIRIK I
ENYU CHANNEL
0.33
1.18
NAUTICAL MILES
1 0 1 2 3 4 5 6 7 8

FIGURE 113.—Shrimp larvae, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

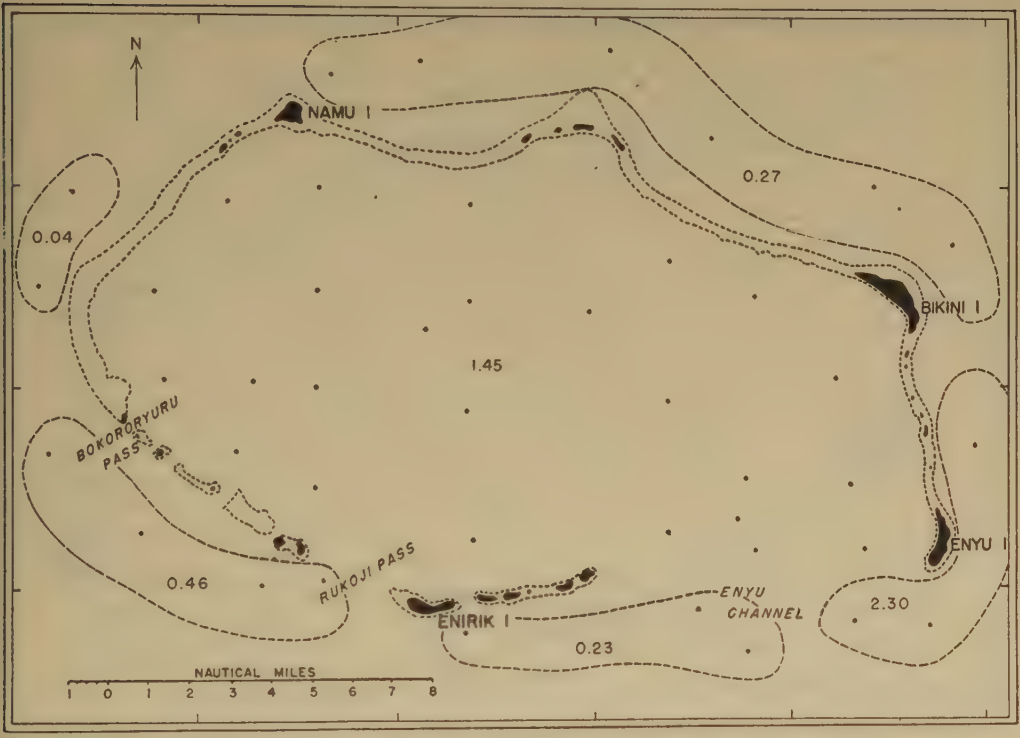

FIGURE 114.—Fish eggs, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

however, there was somewhat of a phytoplankton "bloom" in process during June 17–22. This gave a perceptible discoloration to the water in some parts of the lagoon. A second visit to the lagoon July 22 to 23 showed the phytoplankton to have diminished considerably, but it was still more abundant than observed in any of the other lagoons during the course of the survey.

The report on bottom sediments does not indicate that siliceous material was encountered. While a considerable quantity of diatom frustules may be precipitated to the bottom during the blooms, the diatoms found in the plankton were for the most part weakly silicified and therefore might add but little material to the sediments. The dominant diatom was *Rhizosolenia* sp., which constituted nearly 100 percent of the diatoms over most of the lagoon. The small northeastern bulge of the lagoon showed a similar bloom of diatoms, but these were strangely nearly all a species of *Chaetoceros*. Diatoms such as *Coscinodiscus* with heavier type of frustules were exceedingly rare in the plankton of all lagoons.

Dinoflagellates formed a substantial part of the phytoplankton and were the dominant photosynthetic forms observed in net collections in Bikini Lagoon.

Judging from the small standing crop of phytoplankton in all of the lagoons, with the possible exception of Rongelap, one is tempted to conclude that the sampling method used failed to reveal a portion of the photosynthetic forms or that production and utilization proceed at nearly the same rate. That the water must produce a fair crop of plants seems evident in view of the rather considerable concentration of zooplankton, including a substantial number of forms such as tintinnids and appendicularia that require very finely divided particulate material either as minute living cells or as detrital particles that readily pass through the meshes of the net.

Among the corals the problem of obtaining food is thought to be met by the presence of zooxanthellae that synthesize utilizable organic substance within the coral tissue. (See Prof. Paper 260–E.) However, this is controversial. Yonge (1951) is of the opinion that the

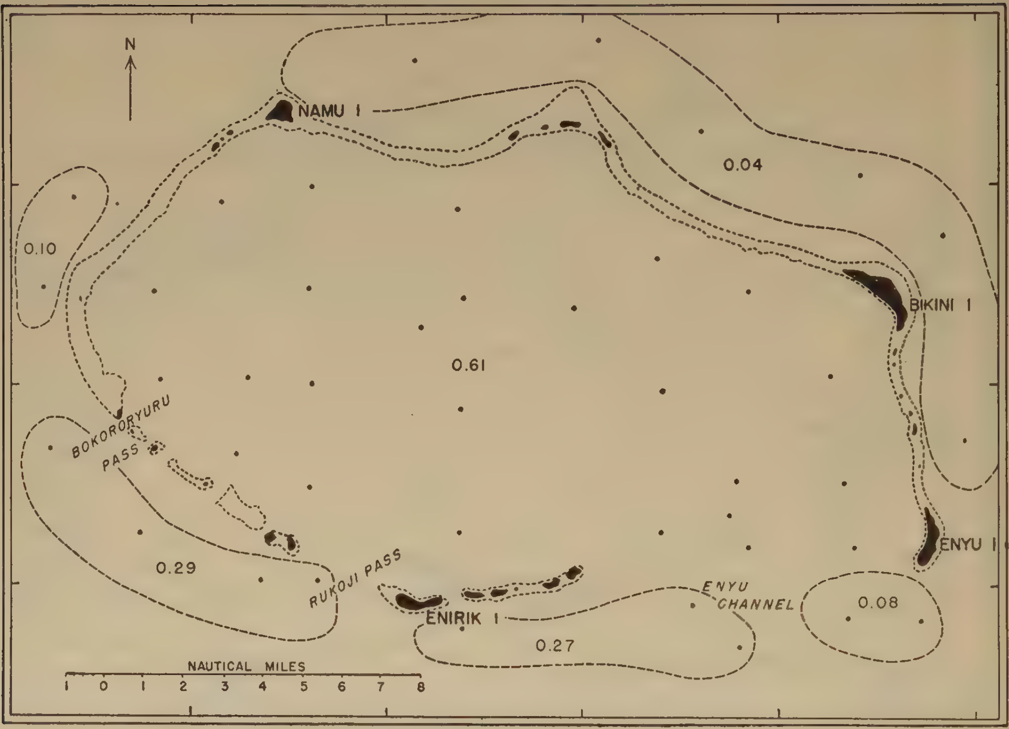

FIGURE 115.—Fish larvae, average number per cubic meter of water by areas; black dots indicate stations averaged in each area.

corals obtain their nourishment from the surrounding water. The zooxanthellae, he believes, are significant mainly in using waste products of the coral metabolism and thus increase the efficiency of the reef-building community of corals.

Whatever the truth may be with respect to corals, it is clear that most planktonic animals must derive their subsistence from the material in suspension in the water since only a few, such as the radiolaria, contain symbiotic algae.

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Biologic Economy of Coral Reefs

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Bikini and Nearby Atolls, Marshall Islands

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-E

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CONTENTS

Page
Abstract 293
Introduction 293
Geographical situation 293
Observations:
  Maximum rate of oxygen production 294
Observations—Continued
  Daily course of rate of oxygen production and consumption 295
  Oxygen exchange of individual reef organisms 297
Literature cited 300

ILLUSTRATION

Page
Figure 100. Daily oxygen exchange 296

TABLES

Page
Table 1. Oxygen production by a reef north of Busch island 294
2. Oxygen production by a reef north of Busch island 295
3. Oxygen exchange on section across reef 296
4. Oxygen content of reef waters 297
5. Rate of production of oxygen 297

BIOLOGIC ECONOMY OF CORAL REEFS

Marston C. Sargent[1] and Thomas S. Austin[2]

ABSTRACT

The eastern reefs of Rongelap Atoll, composed of animals and attached algae, produce more organic matter than they consume. The productivity per unit area is considerably higher than that of adjacent waters or any other open marine areas. The zooxanthellae of the corals make a substantial contribution to the whole production, so that per unit of weight, actively growing reef corals may photosynthesize as fast as lithothamnia. Review of work on other coral reefs indicates that these communities are generally self-maintaining.

INTRODUCTION

The coral atolls of the northern Marshall Islands are examples of a distinctive pelagic community of the Pacific Ocean. For thousands of miles in all directions they are surrounded by the communities common to all open oceans, of which the conspicuous members are plankton, fish, and birds. Only at some singular spots have a succession of crustal movements and biotic changes produced structures and biocycles strikingly different from their surroundings.

In one important respect the situation of these atolls is different from that of any coral reef where extensive studies in physiology and ecology have been conducted. Unlike fringing and barrier reefs, the reefs of these atolls are exposed to a steady one-directional wave-driven current of oceanic water as described by Von Arx (1948). As in a river, changes in the organic and inorganic content occur in this water as it crosses the reef, and if these changes are measured, conclusions can be drawn about the activities of the reef community. The most fundamental conclusion drawn from the observations recorded here is that atoll reefs are essentially self-sufficient communities, producing as much organic matter as they consume, or more. This is not necessarily true of barrier and fringing reefs where proximity of the land and stagnation of the waters overlying and adjoining the reefs may furnish conditions suitable for production of food of reef-building organisms quite independently of the presence of the reef. It may, however, be true of these reefs also, but not be easy to discern under the conditions prevailing.

In a previous brief report (Sargent and Austin, 1949) we have referred to reviews by Yonge (1940) and Shepard (1948) as covering the literature on coral biology and the geology of atolls. To these should be added several reports by Tracey, Emery, Ladd, and others on the geology of the northern Marshall Islands, which will be referred to below. Taylor's volume (1950) on the plants of Bikini Atoll also contains much unique and valuable information.

GEOGRAPHICAL SITUATION

In the present study several sets of measurements were made at two locations on the eastern reef of Rongelap Atoll and one set on the western reef. The morphology of these reefs is described by Tracey, Ladd, and Hoffmeister (1948) in a report which clearly demonstrates that it is difficult to draw a line between the geology and the biology of these structures or communities. Most measurements were made on the open reef between islands where the passage of water between sea and lagoon is unimpeded.

The eastern reef, in the classification of Tracey and others (1948), is type I–A. The smooth marginal *Lithothamnion* ridge rises only about a foot above the main reef flat and slopes gently seaward without development of high-standing buttresses. On the seaward face of the reef below low tide, spurs covered with living lithothamnia and corals and separated by grooves floored with debris reach to a depth of perhaps 15 meters. Behind the *Lithothamnion* ridge, generally 5 to 15 meters wide in these situations, is a roughly triangular zone of coral, narrow where islands approach closely to the *Lithothamnion* ridge but reaching back several hundred feet from the surf zone in the intervals between islands. The remainder of the reef to the lagoon edge is relatively barren of large fixed colonial creatures. Isolated coral colonies and small tufts of

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algae project above the layer of sandy Foraminifera and inconspicuous matted algae that cover the flat. The total width of the reef at the locations studied is about 300 meters. Close to the islands on each side of an interval the reef is higher, exposed at low tide except for numerous tidepools, and largely devoid of life. This barren intertidal zone is in striking conrast with the densely populated intertidal zone of cooler seas.

The transport of water across the reef depends on the stage of the tide. The velocity change does not affect the transport as much as the change in depth. At low tide the *Lithothamnion* ridge may in spots be momentarily awash between breakers, and over the whole flat the depth may not exceed 20 centimeters. At high tide the depth on the flat may be more than a meter. The velocity over the reef flat meanwhile changes perhaps threefold with a minimum velocity around 30 centimeters per second. Depths were determined with a meter stick or, when necessary, by measurements on an observer who was carefully calibrated for the purpose. Velocities were measured by timing the passage of a small patch of fluorescein along a measured line. At this time of year (June–July) the surface of the water flowing across the reef is smooth except close to the surf zone, although no doubt at seasons of high wind it is commonly marked by whitecaps. The smoothness of flow is important for the measurements of changes in oxygen content in that it diminishes any tendency to establish equilibrium with the atmosphere. The flow occurs in pulses resulting from momentary changes of head as the breakers pile up on the face of the reef.

The western reef on which a few observations were made is type II–B–(1) according to the classification of Tracey and others (1948). The coral and algal reef with a steep front facing the sea and precipitous edges where blocks have been broken out has its highest level on the ocean side in the zone of weak surf. It gradually slopes down toward the lagoon, with larger and higher pinnacles or islands of corals growing on it as the bottom gets deeper. On the day of our measurements there was a westerly wind, rare in these latitudes, which was sufficient, together with the tidal change, to maintain a considerable current in an easterly direction. We do not therefore feel qualified to describe typical current conditions on this reef and can only refer to Von Arx (1948), who observed that the direction of the current alternates with the tides.

OBSERVATIONS

MAXIMUM RATE OF OXYGEN PRODUCTION

As the water flows across a reef, particularly at low tide, it undergoes changes in temperature and oxygen content. Table 1 shows the extent of these changes during a noon low tide north of Busch island on the eastern reef of Rongelap Atoll. The two lines were run from north to south parallel to the reef face from a point where the current near the seaward edge of the reef flowed southerly around the end of an island to a point on the other side of the interval between islands where it ran northerly around the end of the next island. It appears that the direction of flow was uniform except at the ends of the line. The velocity was highest in the middle of the interval, and less close to the islands.

At the four stations sampled near the surf zone, the temperature and oxygen content (as determined by Winkler titration) were uniform. Along the inner edge, both the temperature and the oxygen content were significantly greater. Particularly near the ends of the line where water was collected which could have run for some distance parallel to the reef before it rounded an island and crossed the reef, were high temperatures and oxygen contents found. In crossing the reef the water temperature increased, on the average, 0.4 C, the oxygen content 0.74 milliliters per liter. As the water was

TABLE 1.—*Oxygen production by a reef north of Busch island*

[Observations at 1100–1300, July 20, 1946]

Seaward edge of reef								Lagoon edge of reef			
Station	Distance between stations (m)	Depth (cm)	Velocity (cm/sec)	True direction of current (degrees)	Water temperature (° C)	Concentration of oxygen (ml/l)	Concentration of dissolved phosphorus (mg-atoms/l)	Station	Water temperature (° C)	Concentration of oxygen (ml/l)	Concentration of dissolved phosphorus (mg-atoms/l)
1	----------	50	19	160	----------	----------	----------	1	28.7	5.28	0.51
2	122	40	25	320	28.4	4.54	0.54	2	28.6	5.04	.45
3	61	40	8	270	----------	----------	----------	3	28.3	5.44	.54
4	137	35	15	270	28.4	4.50	.51	4	28.8	5.05	.47
5	146	40	34	270	----------	----------	----------	5	28.7	5.06	.[illegible]
6	271	25	31	275	----------	----------	----------	6	28.9	5.05	.49
7	61	35	29	260	28.3	4.53	.66	7	29.4	5.55	.48
8	70	35	34	250	----------	----------	----------	8	29.0	5.77	.31
9	73	35	34	250	28.4	4.58	.51				
10	73	35	17	350	----------	----------	----------				
Mean	----------	35	24	----------	28.4	4.54	----------	Mean	28.8	5.28	----------

saturated with oxygen when it left the surf zone, the increase can be attributed only to photosynthesis by the reef organisms. The product of the mean depth in centimeters, the mean velocity in centimeters per second, and the mean change in oxygen content in milliliters per cubic centimeter,

$$35\times24\times10^{-3}\times(5.28-4.54),$$

gives the mean rate of oxygen production of the reef-top community as 0.62 milliliters per second per centimeter of reef normal to the current. This can be visualized as the oxygen production of all the organisms on a strip of reef top 1 centimeter wide running from surf to lagoon. A more elaborate calculation involving averaging individual products of depth, velocity, and oxygen change gives about the same numerical result (0.63 ml/cm/sec), but it is not otherwise justified by the nature of the data.

As the reef top is about 270 meters wide, the rate of oxygen production can be restated as 23×10^{-6} milliliters per second per square centimeter of reef surface.

The line of stations in the surf zone was on top of the *Lithothamnion* ridge; consequently, only photosynthesis by the reef-top organisms lagoonward from the line was included in the measurement. Oxygen produced by the outer portion of the ridge and by the organisms of the seaward reef face was already dissolved before the water crossed the outer station line. Because of the large volume of water available and the effectiveness of the surf in maintaining oxygen-exchange equilibrium with the atmosphere, no measurable change in oxygen content due to activity of organisms could be expected seaward of the line. The measured increase in oxygen content was therefore found in what appears to the eye as an area rather barren of plants. Besides the *Lithothamnion* of the ridge, the only other plants readily apparent are scattered small erect Rhodophyceae (*Liagora* sp.) 5 to 10 centimeters high and 20 to 50 centimeters apart. Careful search shows that matted filamentous Myxophyceae and other minute algae are common embedded in the foraminiferal sand and in other locations somewhat protected from direct sunlight (Taylor, 1950, p. 11, 102–103). The most striking oxygen-producing organisms of the reef top, however, are undoubtedly the zooxanthellae of numerous corals, tridacnids, and other animals.

By contrast, the outer portions of the *Lithothamnion* ridge and the spurs on the face of the reef appear to be almost completely paved with dark red lithothamnia and we are tempted to assume a much higher rate of oxygen production per square centimeter of reef surface than the average for the reef top. The light intensity at a depth of 15 meters is probably 20 percent of that just below the surface and is presumably adequate for maximum photosynthesis. The circulation of water is rapid (Munk and Sargent, Prof. Paper 260–C, p. 278); consequently the supply of gases and nutrients is as good as at any point on the reef top. The assumption that the reef face is at least as productive as an equivalent area of the most productive part of the reef top is not unreasonable. The area of this zone is such that it may add another 25 to 50 percent to the total oxygen production of the reef.

Table 2 shows additional data on conditions at this station in late morning on other days. The averages from table I are included for comparison. It appears at once that individual observations on the increase in oxygen lie within the range of individual observations made nearly simultaneously along a single stretch of reef. On June 30, when observations on depth and current velocity were made, the calculated rate of oxygen production was quite comparable with that on July 20.

Data shown in table 3 for another station also support the view that this value does not vary widely for reefs of similar characteristics and dimensions.

TABLE 2.—*Oxygen production by a reef north of Busch island*

[Quantities marked by an asterisk (*) are averages]

Date	Time	Dissolved oxygen (ml/l)			Depth (cm)	Velocity (cm/sec)	Rate of oxygen production (ml/cm/sec)
		Seaward edge	Lagoon edge	Increase			
June 29	0940	4.51	5.95	1.44			
June 29	1130	4.46	4.90	.44			
June 30	1120	4.55	5.47	.92	20	49	0.90
July 20	1100–1300	*4.54	*5.28	*.74	*35	*24	.62

The single set of data for a station on the western reef shows that the oxygen content increased 0.10 milliliter per liter at noon when the water was 107 centimeters deep at a point where the velocity was 40 centimeters per second. The calculated oxygen production was 0.49 milliliters per second per centimeter of reef normal to the current. This oxygen change occurred over a considerably narrower reef than that at Busch island. In any case, the rate of production of oxygen appears to be of the same order of magnitude even on somewhat dissimilar reef areas.

DAILY COURSE OF RATE OF OXYGEN PRODUCTION AND CONSUMPTION

These measurements show the rate of oxygen production by the reef community at noon. What is the daily cycle of changes in this rate? Measurements of this kind are not easy to make except at low tide. Whenever the water on the reef is deep, and the velocity great, obtaining samples is more difficult, and the differences in oxygen content between different samples diminish until they approach the experimental errors.

Table 3 and figure 100 show the results of a set of observations made near Bokujarito island on the eastern reef on a line of four stations across the reef throughout a period of over 24 hours. It is clear that qualitatively the cycle of events was what would be predicted. The rate of oxygen production was highest around noon, and comparable with the rate at Busch island and on the western reef, while at night there was a considerable use of oxygen by the respiration of the reef organisms. Some parts of the curve in figure 100 are drawn on the basis of reasonable assumptions such as that the rate of respiration is constant all night and photosynthesis begins about sunrise. The diurnal variation in rate of photosynthesis, as plotted, differs from the variation in insolation in that the rate of photosynthesis is relatively lower in the afternoon hours. There are previous reports (Kostytschew *et al.* 1926, 1930) that under natural conditions, rate of photosynthesis of both land and water plants reaches a maximum before noon and then declines; Yonge, Yonge and Nichols (1932, p. 226) observed this in reef corals. Some observations of our own, described below, support this.

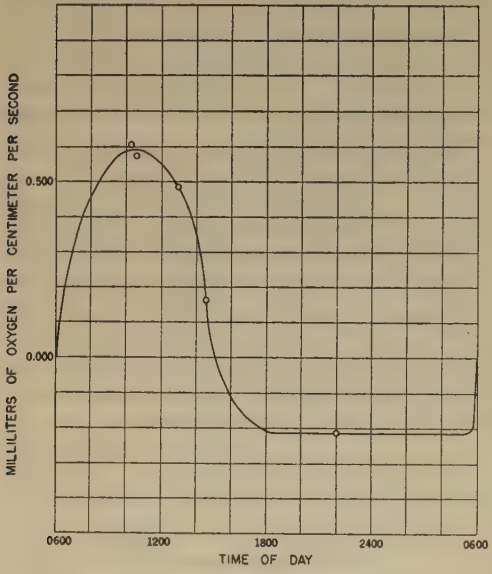

FIGURE 100.—Course of daily oxygen exchange of reef.

Graphical integration of the two arms of the curve shows that during the daylight hours 14,000 milliliters of oxygen were produced per centimeter of reef. During the night, 11,000 milliliters of oxygen were consumed. During the 24 hours there was then a slight excess of organic matter formed equivalent to 3,000 milliliters of oxygen per centimeter of reef. Table 2 shows that at Busch island the rate of oxygen production at noon was probably at least as high as at Bokujarito island. The one usable set of night observations at Busch island gives an oxygen-consumption rate of only 0.10 milliliter per centimeter per second.

Assuming that

$$CO_2+H_2O=CH_2O+O_2,$$

where CH_2O stands for the organic matter produced by photosynthesis, and less accurately, for organic matter in general, it follows that 3,000 milliliters of oxygen produced is equivalent to 1,600 milligrams of carbon fixed as organic matter. The reef width at this point is 300 meters, and a 1-centimeter strip equals 3 square meters. The fixation of carbon as organic matter therefore amounted to 500 milligrams per day, or 190 grams per year, per square meter. As there is no indication that the reef rock contains any such proportion of organic matter as this would indicate (Ladd, Tracey, and Lill, 1948), we may suppose that this amount of material is formed on and removed from the reef annually. This removal may be continuous, in the

TABLE 3.—*Oxygen exchange on section across reef at Bokujarito island, June 17–18, 1946*

Date and time	Station 1 (surf zone)			Station 2	Station 3	Station 4 (inner edge) oxygen content (ml/l)	Change in oxygen content (ml/l	Rate of oxygen production (ml/cm/sec)
	Oxygen content (ml/l)	Depth (cm)	Velocity (cm/sec)	Oxygen content (ml/l)				
June 17								
1020	4.21	18	35	4.85	5.19	----------	0.98	0.62
1150	4.25	----------	----------	4.50	4.77	4.80	.55	----------
1440	4.28	64	84	4.34	4.31	4.31	.03	.16
1750	4.31	----------	----------	4.23	4.27	4.29	−.02	----------
2200	4.09	18	[1] 35	4.03	3.94	3.74	−.35	−.22
June 18								
0100	4.19	----------	----------	4.27	5.02	----------	−.17	----------
0400	[2] 4.26	----------	----------	----------	[2] 4.25	----------	−.01	----------
1030	4.49	20	73	4.57	4.67	4.88	.39	.57
1255	4.42	36	78	4.57	4.58	4.59	.17	.48

[1] Estimate.

[2] Position approximate.

form of dissolved or fine particulate organic matter, or occasional and catastrophic during storms or high waves which break off whole colonies or large blocks encrusted with living organisms. Water flowing off the reef is limpid, remarkably free of plankton or any other sediment, and has a low biochemical oxygen demand (see Johnstone's data in Sargent and Austin, 1948). We therefore incline to the belief that removal of organic matter from reef or lagoon is occasional. Loss to the outer talus slope probably does not enter our calculations because these cover only the interval from the inner edge of the surf zone to the lagoon.

One other quantity of interest is the gross rate of photosynthesis—that is, the sum of the apparent rate of formation and the concurrent rate of consumption of oxygen. We have no way of deciding how much of the measured oxygen consumption is due to animals and how much to plants. We will guess that less than half of it is due to plants, but lump it all together in estimating the gross production rate.

During the daylight hours, 14,000 milliliters of oxygen were produced per centimeter of reef. Assuming that the day lasted 12 hours, a respiration rate of 0.22 milliliters per centimeter per second concurrently consumed 9,500 milliliters of oxygen per centimeter. The gross rate of production per day was then 23,000 milliliters of oxygen per centimeter. Using the conversion factors above, the equivalent in carbon amounts to 1,500 grams per square meter per year. We have shown previously (Sargent and Austin, 1949) that this is much higher than the production rate in the adjacent ocean and lagoon waters. According to Riley's compilation (see Sverdrup, Johnson, and Fleming, 1942, p. 938) of production rates, it is higher than that of any open waters where measurements have been made. General impressions lead us to believe that some estuarine areas and, in temperate zones, rocky shores between tides and to depths of a few dekameters may be as productive as these reefs, but we have no exact observations.

OXYGEN EXCHANGE OF INDIVIDUAL REEF ORGANISMS

Oxygen was produced by all parts of the reef from the surf zone to the lagoon edge. Table 4 summarizes data taken towards midday on lines of stations crossing the reef. On each line, station 1 was on the *Lithothamnion* ridge, station 2 was well back in the zone of rich coral growth, station 3 was in the apparently barren back part of the reef, and station 4 at the lagoon edge. Although there is great irregularity in the data, it is apparent that, on the average, oxygen was produced in each zone. Although the individual plants of the lagoonward reef flat are not conspicuous, their combined productivity is considerable.

Three sets of observations were made on the activities of individual organisms. Table 5 shows the maximum rate of oxygen production, in milliliters per gram per hour, of *Pocillopora*, *Acropora*, and *Porites*, three reef corals; *Porolithon*, the characteristic lithothamnioid of the surf zone; and *Liagora*, an alga of the reef flat.

TABLE 4.—*Oxygen content of reef waters, in milliliters per liter*

Date	Time	Oxygen content for station—			
		1	2	3	4
Bokujarito island					
June 17	1020	4.21	4.85	5.19	-------
	1148	4.25	4.50	4.77	4.80
June 18	1020	4.49	4.57	4.67	4.88
	1255	4.42	4.57	4.58	4.59
June 20	1220	4.28	4.34	4.44	4.41
Busch island					
June 29	0940	4.51	5.18	5.06	5.95
June 30	1120	4.55	5.32	5.04	5.47

TABLE 5.—*Rate of production of oxygen by corals and algae*

Specimen	Air-dried weight (g)	Rate of oxygen production (ml/hr) for indicated time of day			Maximum production rate (ml/g/hr)
		1015–1045	1045–1300	1300–1400	
Liagora	3.1	0.70	0.30	0.48	0.23
Porolithon	2.4	.11	.02	.09	.046
Pocillopora	11.3	.84	.16	.28	.075
Acropora	14.3	1.68	.34	.56	.118
Porites	13.2	.56	.20	.31	.042
Pocillopora	16.0	.36	.37	.56	.035
Control water	-----------	0.00	−0.04	0.02	-----------

The method of measurement was extremely simple. Samples were selected on the reef at low tide. Water was collected in an enameled pail, and the water stirred gently but thoroughly. The samples were put in pint mason jars; these jars were filled by gradual immersion in the pail, and the caps were screwed on under water so that bubbles were excluded. Also samples of water without added organisms were bottled, and samples were taken for immediate analysis. Each mason jar was then laid on its side in flowing water on the reef and propped in place with pieces of reef rock when necessary. During the exposure the temperature in the jars did not rise significantly above the surroundings (28–29°C). At the end of the exposure, each mason jar was shaken gently and a water sample (200 ml) siphoned off into a glass-stoppered bottle for oxygen measurement. The jars were then emptied and filled with freshly collected water for the next measurement. In order to save time and to keep the samples under as natural conditions as possible during the whole set of measurements, all these operations were carried out on the open reef. Winkler reagents were added to the water samples within 20 minutes after they were drawn. The small activity found in the water indicates that this delay had no serious consequences.

The organisms collected as samples were selected as representatives of dominant members of the communities on different parts of the reef. The *Porolithon* was collected as far out in the surf as possible. The three species of corals—originally collected as four—occurred in the zone of abundant coral growth behind the *Lithothamnion* ridge. The *Liagora* is the most conspicuous alga of the lagoonward reef flat, where individual bushy plants a few centimeters high occur with a density of growth sometimes as high as 20 per square meter. According to Taylor (1950, p. 118), members of this genus are not as common at other times of year.

The coral samples and the *Porolithon* were in all cases single pieces taken from the tops of actively growing portions of the colony, apparently in good condition, very clean, and with no visible overgrowth of sessile organisms. The *Liagora* was essentially a whole plant about 5 centimeters high. All these samples consisted of a small amount of living tissue and a relatively massive deposit of lime. In *Liagora*, the ratio of tissue to skeleton was undoubtedly much higher than in the other organisms, and this is reflected in the relatively large oxygen production per gram.

Table 5 shows the results of a measurement of the relative maximum rates of oxygen production of the various organisms. The three measurements were made late in the morning, at noon, and early in the afternoon. Although there is no way of checking the results, we are sufficiently practiced in the technique to feel confident that the apparent differences in rate represent real differences in activity rather than inadequacies in the mechanics of measurement. For instance, the lower activity at noon appears to be real and is probably an aspect of the phenomenon, observed by Yonge and others (1932), and by us (fig. 100), that activity reaches a maximum during the morning. To what extent the differences in activity reflect responses to differences—of which we were unconscious—in our manipulation of the individual specimens, we cannot say. Yonge (1937) has pointed out that some species of corals, notably members of the genus *Acropora*, yield quantities of mucus under handling and that the rapid consumption of this material by bacteria may give spurious values for the respiratory activity of the coral. In table 5, however, *Acropora* shows a suprisingly high rate of oxygen production. Because in general our observations of this genus were over such short intervals, and because the oxygen production rates so large, corrections for bacterial respiration should be only of secondary importance.

As shown in the last column of table 5, the maximum rate of oxygen evolution observed per gram of sample does not vary widely between the three species of corals or between the coral species and the alga *Porolithon*. Observations on *Liagora*, which is relatively slightly calcified, give a much higher value.

The data of Yonge and others (1932, pp. 224–228) recalculated to milliliters of oxygen per gram per hour (assuming a specific gravity of 2.5 for coral) include a range of values from 0.031 to 0.001—that is, all are somewhat lower than our values, some much lower. However, there is a clear inverse correlation between activity and size in their data, which was obtained with pieces of coral weighing from 15 to 80 grams, indicating probably that the larger pieces had lower activities because more dead coral was included. The heaviest of our pieces weighed 16 grams and all were heathy, presumably growing, tip pieces. Kawaguti (1937), using small pieces of coral, found activities as high as those we have observed. Therefore, our values for maximum rate of oxygen production by corals probably are dependable.

Only repetition of the measurements with careful selection of specimens of the alga would show how much importance should be attached to the fact that *Porolithon* had a rate of photosynthesis no higher than the corals. We also recognize, as did Yonge and others, that the activity per gram or per cubic centimeter is not a satisfactory unit for comparative studies.

Discussion.—We have previously shown (Sargent and Austin, 1949, p. 246) that the rate of consumption of organic matter by the reef community as measured by the oxygen consumption is much larger than the rate of supply of organic matter by the current driven across the reef. Neither the amount of material caught by a plankton net nor the amount available for oxidation by bacteria in the biochemical oxygen-demand measurement is sufficient to satisfy the requirements of the reef community. We have further found that between the surf zone and the lagoon the reef community as a whole produces in a 24-hour day probably somewhat more organic matter than it consumes. The picture of the reef as a self-supporting community, depending on the current only for dissolved nutrients (in a broad sense), and not for particulate or dissolved organic matter, is reasonably clean cut.

This may be true of the Great Barrier Reef, studied by Yonge and his associates, and of the coral reefs in the Bay of Batavia, studied by Verwey (1931). The absence of a steady current across the reef from the open sea at these locations makes the solution much more difficult. In each of these cases there is an adjacent land mass and a relatively stagnant lagoon to complicate the study of the situation. The growing reef edge even here, however, might exist only in a current of open ocean water maintained by the head piled up on the reef by surf. In this case it could turn out that these reefs also are self-supporting.

Our few experiments and the more numerous and more carefully performed ones of Yonge and others (1932) show that the contribution of the zooxanthellae of the corals to the total productivity of the reef is far from negligible. There is no doubt that in many cases the rate of production of organic matter by the zooxanthellae of a coral colony is quite sufficient to support the whole colony. Yonge and others (1932, p. 234) found that 17 out of 22 colonies sealed in jars survived 14 days, and at the end of this time had not exhausted or had barely exhausted the oxygen in the jars. As long as nearly as much oxygen remained at the end of the experiment as was available in the beginning, there must have been nearly as much organic matter present at the end as at the beginning; that is, unless the original piece of coral colony was very small, or its respiratory activity very low, organic matter must have been produced by the zooxanthellae at a considerable rate or in any case almost as fast as it was consumed by the whole colony. In 6 of their 17 surviving colonies, there was more oxygen in the water and hence more organic matter in the jar at the end of the experiment than at the beginning. In another of their experiments (Yonge and others, p. 222), only 1 of 29 colonies produced more oxygen than it consumed in 24 hours. However, in another experiment (Yonge and others, p. 218) 8 of 22 specimens had a higher rate of oxygen production during 9 hours in the light than during 9 hours in the dark, and there is a reasonable possibility that 12-hour exposures would have given the same results in most cases. In other words, during a natural 24-hour day these colonies would have produced more oxygen than they consumed. Yonge and others, (1932) point out the possibility that epiphytic algae, or phytoplankton in the 14-day experiment, could have contributed to the apparent oxygen production. It should also be pointed out that bacterial activity, especially in the experiment lasting 14 days, could have consumed organic matter and oxygen at a rate sufficient to mask production by the zooxanthellae wholly or in part. Verwey (1931, pp. 175–176) found that pieces of coral colony produced as much organic matter as they consumed. The observations of Kawaguti (1937, p. 196) on the ratio of oxygen consumption to the rate of oxygen production also lend color to this view. The sum of this evidence is that the zooxanthellae of corals produce organic matter at a rate quite comparable with its rate of consumption by the coral colony, under favorable circumstances probably exceeding it.

There is additional reason to believe that the reef corals not only could subsist on the products of their zooxanthellae but do. The product of the photosynthesis of the algae appears to remain within the coral colony. Evidence that organic matter produced on the reef remains there was presented on p. 297. In the 14-day experiments of Yonge and others (1932), no mention is made of large bacterial growth which would have indicated that the products of photosynthesis were being secreted by the coral colony. The results of these experiments strongly indicate a high rate of activity and a practically closed cycle of events within the colony.

What is true of the reef community as a whole appears now to be true of individual coral colonies. The external supply of organic nutrient is inadequate to support a coral colony on the reef, but the daily production of organic matter by its contained zooxanthellae can be sufficient. Although Yonge (1940, p. 365) has reviewed his own careful work and other data indicating that corals do not derive organic matter directly from their zooxanthellae, we believe that the weight of evidence is on the opposite side. Under conditions of growth on the eastern reef of Rongelap Atoll, the association between corals and zooxanthellae seems to be essential to the individual colonies precisely because the corals must derive organic matter from the algae or die.

This brings up another general question: zonation on the reef. As described by Tracey, Ladd, and Hoffmeister (1948), the reef top is composed of zones parallel to the edges. Behind the *Lithothamnion* ridge is a zone of rich coral development and behind this a reef flat populated principally by very small organisms. Our observations indicate that the temperature difference between the two sides of the reef even at low tide is relatively insignificant. In tide pools and backwaters around the islands large temperature differences occur, but not across the open reef between islands. The oxygen differences are likewise insignificant, and we believe that differences in carbon dioxide content and associated pH would be no greater. The possible gradient in organic matter. suspended or dissolved, is limited to a very small value by the absence of organic matter in the source water from the open sea. The difference in phosphate content (table I) is so small as not to be certainly measurable. The sediment load of the current is so small as to appear negligible.

Munk and Sargent (Prof. Paper 260–C, p. 278) have suggested that *Lithothamnion* grows luxuriantly only in the zone of violent surf because of the scrubbing action of the momentary high-velocity currents which can remove various solids and also rapidly renew the water lamina close to the surface of the algae. Almost the only factor we can imagine varying sufficiently to account for the limitation of distribution of coral colonies is also velocity of moving water. The current velocity along a line across the reef does not vary much because the depth along the line is nearly constant inside the *Lithothamnion* ridge, except close to the lagoon edge where it begins to deepen. However, the average wave height and frequency diminish with increasing distance from the seaward edge, and below some critical value for these quantities conditions for growth of coral may become extremely unfavorable.

The fact that the reefs are more productive per unit area than the surrounding waters we have previously ascribed (Sargent and Austin, 1949) to a higher overall efficiency of attached compared with planktonic algae. We have no further evidence in support of this speculation, but we can find no other ultimate reason for the flourishing of coral atolls in an empty ocean.

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Proceedings
# of the Fishery Products Conference
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Service Research and the Fishing Industry

By John L. Farley,
Director, Fish and
Wildlife Service

It is a pleasure to meet with a group whose members have done so much to add to the enjoyment and ease of good living. You devote your lives to preservation of foods by canning; I represent an agency of government that devotes itself to the preservation of the productivity of the raw material which is the basis of your industry.

Thus the word "preservation" expresses an idea which each of us fosters, though from different points of view.

The preservation of foods by canning had its earliest beginnings as an art, and through industrial research has gradually evolved into an exact science. Thus you have learned how to control the quality of your product by the application of formulae which time and experience have proven to be dependable. We are striving for a similar goal. I say "striving" because the preservation—or conservation as it is more commonly called—of the productivity of fishery resources is still a science-in-the-making. One of the principal functions of the Fish and Wildlife Service is to further the development of that science through study of the living fishery stocks as they are affected by fishing. The goal of our scientific staff, of course, is to provide the information required for rational direction of fisheries, and it is the task of administrators to translate that information into practical application which usually takes the form of regulations.

As I get deeper into the job of making decisions about regulations, I find unexpected complexities, for problems relating to the affairs of men must be considered as well as those relating to stocks of fish. Consequently, issues which are not often as crystal clear as we would like them to be, demand all the careful, wise analysis that we can bring to bear on our judgments.

Here let me add my word of welcome to Arnie Suomela, our new Assistant Director, who is going to play a very important part in making those judgments. Those of you from the Pacific Northwest need no added words of mine to have you know Arnie Suomela; he has been part of you for so long. He is a prominent scientist. As an employee of the former United States Bureau of Fisheries he served in Washington and Alaska. Since then he has served the State of Washington and, more recently, he left the State of Oregon where he was Director of the State Department of Fisheries, to accept a position which we encouraged him to accept here. We feel we have a valuable asset in Arnie Suomela. He is going to share some of this burden that I have carried, and be able to act, in many cases, with much more assurance and certainty than at times I have felt; and I shall rely heavily upon him.

I have said that regulation of fisheries must take into account not only fish but men. This was brought vividly home to me recently in a problem which we have had to deal with in Alaska in considering the annual regulations.

We saw earlier this afternoon a chart of the world distribution of herring. This fish is widespread throughout the northern hemisphere, and sometimes and in some places is an enormously productive resource. However, that seems to be not its condition at present in Alaska.

When we started on the regulations I paid no particular attention to the herring fishery, for it had seemed relatively unimportant. But I did look at the records; and found there had been a herring fishery in Cook Inlet which had disappeared, a herring fishery around the Kodiak area which had practically disappeared, a herring fishery in the Prince William Sound area which had practically disappeared, and a herring fishery in Southeastern Alaska whose yield had dropped from over 400,000 barrels to less than 100,000 barrels and had remained at that low level during five seasons.

I found some rather disturbing information that spawning areas had become reduced. What would you do with that information? Stand by and do nothing and perhaps let another herring fishery disappear from Alaska? Or should you do the thing that looks reasonable and practical—the only thing that you could do? Preserve the remnants that were there in the hope that the added spawning effort might contribute to a more rapid recovery?

But in keeping with what I consider an obligation of the Fish and Wildlife Service—that, where possible, regulations should be based neither on a capricious snap judgment nor even on well-organized thinking, but rather on biological facts—I requested more information. I was really amazed at the added amount of it which our biologists brought forth. So I found some of these things you have been hearing about this afternoon, which must be taken into account in for-

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mulating regulations. It appears that factors besides the amount of spawning influence the abundance and accessibility of herring. Furthermore, our biologists point out that it is desirable to retain a sampling of the stocks, so as to maintain a means of assessing their commercial possibilities.

Then involved in all this is an issue which has become a highly emotional matter in Southeastern Alaska. In preparation for the Seattle hearings, I made a quick trip to Juneau, Ketchikan, Wrangell, and Petersburg to meet with the fishermen. From their point of view everything that was wrong with the salmon trawling was due to the herring fishery. That became the focal point of our discussion; and all that those fishermen said we studied very seriously along with all of the facts which we could dig out of our records about herring. Thus we have considered this herring case from every point of view, and when our decision is announced, you may be sure that it is as right as our most careful judgment has been able to make it.

Although people do not always unanimously approve of the choice of regulations, they generally do agree to the necessity of some action to conserve the resources. Here I must pay tribute to the way in which members of the industry and the fishermen have cooperated in a 50 percent reduction of traps in Southeastern Alaska for next year. This means 50 percent reduction of the effective areas for fishing; and this program will continue for two years because it looks as if there will be two bad years. Giving up so much following such a bad season as the last means a lot to fishermen and operators; and that is why we so thoroughly appreciate their cooperation.

In the background of all regulations for conservation is the work of researchers. Ours is primarily a research agency. The Service was founded on research, and it will continue to foster research. Over the course of a number of years, I have had ample opportunity to observe researchers at work in two governmental agencies, state and federal; and also have seen something of them in private industry. They are interesting people. They have carried into their mature years the youthful urge to ask questions and get answers. The practical need of the answers is sometimes secondary with them. Their primary interest is to extend or fill in the gaps in their present field of information. They find an unusual joy in discovery. When after long hard work they find at last something they have been looking for, whatever it may be—the answer to a problem, the formula to a chemical, the spawning grounds of a fish—they have a way of announcing their discovery modestly in the sometimes incomprehensible language of science, then putting it aside and starting a search for something else. They never slake their thirst for search. At least, they don't if they are any good. One exasperating thing about scientists is that they often don't stop their search soon enough. Just when they seem to have uncovered great new avenues of knowledge, they look a little further, and discover more ignorance which needs further investigation than we had been aware of. No matter how long they work, they always see more questions to study.

We hear much discussion about the difference between pure research and practical research. I am not particularly excited about that. I don't know where one begins and the other ends. When we get to the point where we start applying the research that had started out as "pure" it automatically becomes "practical"; and if it can't ever become practical, then we as businessmen are not quite so interested in it. The first step of any scientific undertaking is not to determine its purity, but to put up to the scientist the right question in the right way. This often determines the whole course of the research. In actual practice, the scientist formulates these questions. He puts a selection of them up to the administrator, and the administrator selects those which are most germane to his public problems. Sometimes, in attacking the selected questions, the scientist finds it necessary to make incursions into the realm of pure science in order to reach principles that can be used in applied science. Here I think the task of the administrator is to find the importance of the pure to the applied, and then to give it all the scope necessary to achieve the goals which we set in our questions.

The most important function of the administrator of an agency like ours is to find men of brains and education who are willing to dedicate themselves to research about fishery problems. We devote a great deal of time to scouting for such people; we spot them in universities sometimes long before they acquire their degrees. We regard the time given to this as a very good investment in the future. Once we get such people, our job is to provide a fertile atmosphere for their doing a superlatively good job.

The administrator discovers very soon that good fishery research is expensive; and there seems to be no limit to the amount of money that scientists could profitably use. At a time when economy is a keynote of government, this poses a very perplexing problem; for it is not possible to carry on research without men and equipment. Some necessary observations can be made only at sea, and must continue year after year; therefore, we can't do without vessels—and I need not tell you how much it costs to operate vessels. The scientist working ashore needs things like analytical balances, spectroscopes, electron microscopes, experimental aquaria, and all manner of special, costly devices. I am continually told about problems that can't be solved without these things. Here the administrator has the thankless job of distinguishing between what is likely to be absolutely essential to the solution of a problem and what is merely a good thing to have to fit out a well-rounded, well-equipped research laboratory.

There is occasionally some controversy as to who is to do the work of research. It sometimes appears to us that all fishery institutions and all fishery scientists would like to have the honor and pleasure of directing and conducting all the research in their respective fields. To some extent this is as it should be. A spirit of competition has a place among research workers as a stimulant; but the place is a very small one. For the truth is, there are far too many fishery problems waiting to be solved, and the problems are far too large for the means that are available, and the number of competent research men is far too small to allow such a question to take on very great importance. To make the best use of such funds, facilities, men and agencies as there are, we must give every possible encouragement to collaboration, bringing all interested groups together in the planning and execution of fishery research programs involving large areas and several jurisdictions. Moreover, every precaution must be taken to assure proper coordination of the work of different institutions so as to obviate overlapping.

In conclusion, I would like to reiterate that I recognize the serious impact which regulations have on industry. I recognize that all too frequently regulations have to be made on incomplete information. At the same time I would like to assure you, that so far as it is humanly possible, it it the aim of the Fish and Wildlife Service to make its administrative regulations responsive to the scientific knowledge that is available, and as reasonable and helpful for a continuing productive fishery as it is possible to devise. That is our aim and that is our service to you.

FLUCTUATING FISHERY STOCKS

Fluctuating Fishery Stocks: What We Know about This World-wide Riddle

**By L. A. Walford, Chief,
Branch of Fishery Biology,
Fish and Wildlife Service**

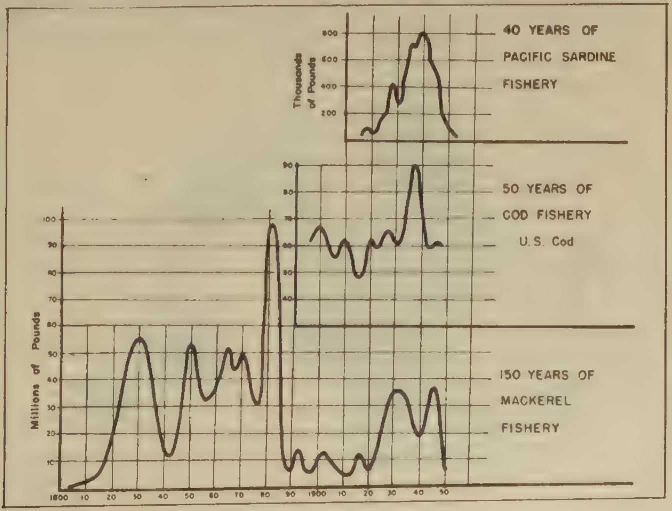
Many of you are concerned about the condition of your fishery stocks, several of which seem to have receded to a low ebb of abundance in recent years. You are asking what has happened to pink salmon, to Alaska herring, to Maine sardines, to the Pacific sardine, to the Gulf of Mexico shrimp. Are there fewer of them in the sea? Or have they perhaps retreated to distant, more obscure areas and become less accessible to fishermen? Whatever the nature of the condition may be, is it permanent? It is not only Americans who are concerned with these questions. So are people in other parts of the earth, for comparable conditions have occurred elsewhere, not only in California, Maine and Alaska, but also in such distant and widely separated places as Japan, India, Spain, North Africa. Is this all the result of mere coincidence? Could any important part of this effect have sprung from some common cause impelled by such a cosmic influence as weather, for example, which might affect these diverse species in a similar way? Are all these recent and current seemingly peculiar conditions within the range of normal variation? That last question is most important, because the seriousness of present conditions can be judged only in comparison with some standard; and that standard, which we call the normal cannot be simply defined.

Part I—The Problem; Some Contributing Factors

In the language of our everyday conversation, the word "normal" tends to have the rather fuzzy meaning of things-as-they-should-be. Lucky is the "perfectly normal man." There is nothing wrong with him. It will be a fine thing when "the country gets back to normal again," when our domestic and international problems have become resolved. When enough food is produced to feed the millions of hungry people of the world, they can enjoy "normal lives." Those are conceptions we hear on every side. In its popular connotation, normal is the good state of affairs, the good life. In the language of the statistician, it is something quite different—not nearly so cheerful a word, but very much more exact. It is simply the average, the sum of all the items divided by the number of items—the lean years and the fat, the good and the bad, the tall and the short—whatever it may be that we are talking about.

We are talking about fishes and invertebrate animals that happen to be commercially useful for canning. Exact information about the history of these species is limited to relatively few recent years when they have lived under the pressures of intense fisheries. We know nothing about their fortunes under virgin conditions. In those days, did they go through alternating periods of great abundance interspersed with periods of contrasting scarcity? What was their normal life then? We cannot tell. A great part of what we can learn now we must deduce from the catches of fishermen. Thus, in searching for normal patterns about the complex lives of fishes in order to understand the significance of events in a single year like the last, we must take into account patterns in the complex affairs of men. The behavior of fishermen fluctuates in response to economic conditions; and for that reason as well as others the intensity of fishing rarely remains constant long. Fishing techniques improve, fishing fleets increase in size, and markets change. And because recorded history about these aspects of fisheries is usually exasperatingly fragmentary, it is difficult to draw absolutely certain conclusions about normal conditions of fish or of fisheries. This much, however, seems clear: conditions have rarely been "normal," as I will show you in these few graphs:

Figure I. Fishery harvests are characteristically unstable, subject to irregular oscillations. This is illustrated in schematic representations of 150 years of Atlantic mackerel fishing, 50 years of American cod fishing, and 37 years of Pacific sardine fishing.



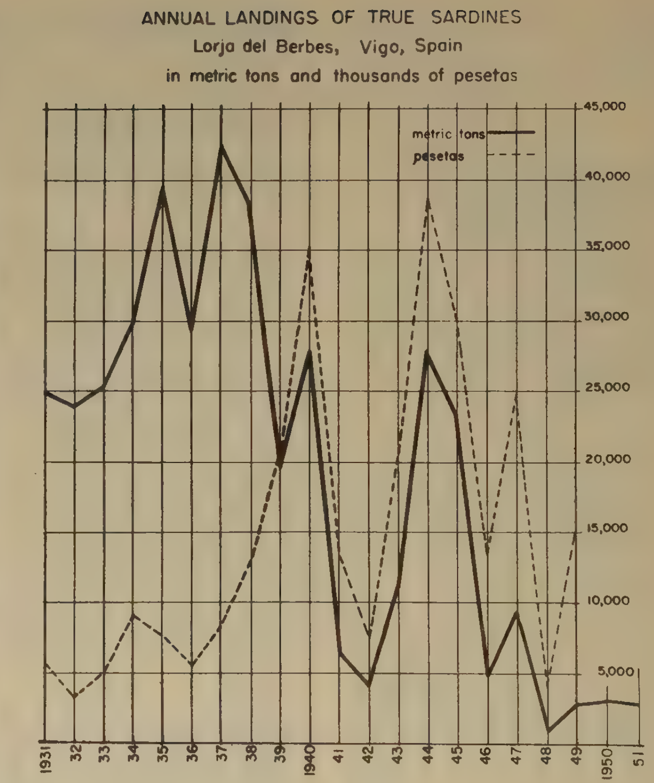


Figure II. A graphic record of 20 years of sardine fishing in northern Spain.

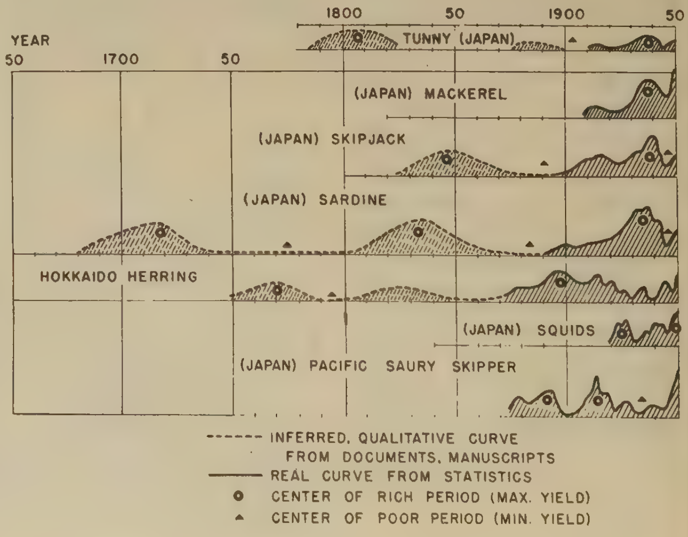


Figure III. In 300 years of Japanese fishing for tunny, skipjack, herring, squid, and saury, periods of abundance alternate with periods of scarcity. Data are not statistically good enough to demonstrate any periodicity in these waves; nevertheless some Japanese scientists interpret that waves of maximal abundance have occurred about as follows: tunny 60 years apart, skipjack 80 years apart, sardine 100 years apart, and Hokkaido herring 50 years apart.

Part of the fluctuations shown in these records reflects economic conditions, part reflects the degree of accessibility of the fish on fishing grounds, and part—surely a very important part—reflects fluctuating abundance of the fish. Fishery biologists work continually to resolve these influences and have made much progress in that effort. They have long been in general agreement that fluctuations in environmental conditions cause fluctuations in abundance of the fish; but what elements of the environment are critical and by what mechanisms they affect the survival of fish, are problems that remain largely unsolved. As long as that is true, fishing must continue to be the uncertain occupation that it is.

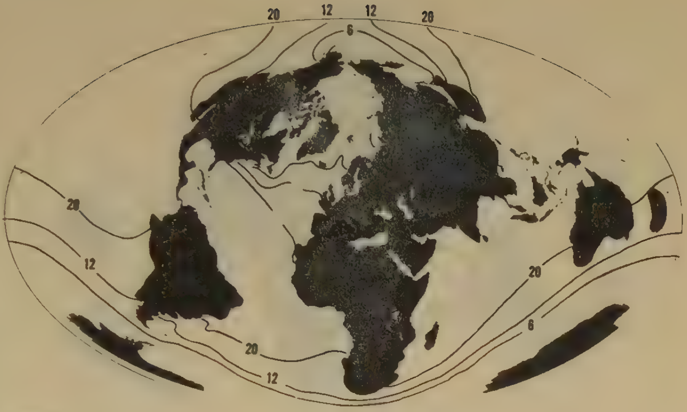
Agricultural science is far ahead of fishery science in understanding the biology of the environment and making use of that understanding. But then, of course, the problems of agriculture, difficult though they may be, are very much simpler than those of fisheries. For the farmer has the enormous advantage over the fishery man of being able to perceive his produce as it develops; and there are various things he can do to protect it when a period of unfavorable weather hits, such as a cold spell or drought. Because the farmer can follow the vicissitudes of his produce with his eyes, he is constantly aware of what is happening on his land. He knows the limits of his piece of the environment and he can put a fence around it which will contain his crops and his animals; and therein they will stay until he is ready to harvest them.

The fishery man enjoys none of these advantages. The environment in which he is most interested, the body of water in which dwell the fishery stocks that give him his living, is continually moving, changing direction, position, levels. Now it is close to the shore, now far at sea, now at the surface, now deep in the depths. It expands and contracts, like a living thing; and as far as we can tell, the fishery stocks which it contains tend always to fill it to its capacity and to remain in it wherever it goes. But its capacity evidently also changes constantly. All the evidence which has accumulated about the natural history of aquatic animals indicates that their environments have limits beyond which they cannot stray very far. How can we define those limits? How can we distinguish a body of water which contains all the materials that attract mackerel from a body of water which repels them?

One of the most obvious boundaries of the territory in which an aquatic animal can live is temperature. Fish are exceedingly sensitive to temperature. I will give you one example to illustrate this point.

Dr. H. O. Bull, a marine biologist working at the Dove Marine Laboratory, Cullercoats, England, became interested in learning just how sensitive a fish is to various qualities of the environment. What does a fish feel? That was the sort of question he asked, a very difficult question because fish feel and respond to many different stimuli. So it was necessary to build special aquaria designed to permit him to exclude all stimuli except the one being studied. So he carried on a number of experiments to test the sensitivity of cod fish to temperature. First he conditioned the fish to associate the presence of food with a change of temperature. Then, having done that, he determined what degree of change the fish would respond to by observing the minimal temperature at which it would perform a complex task in order to get food. He kept the fish in a specially constructed tank with the floor inclined so that one end was deep enough to provide a habitable living space and the other end extended out of the water. He introduced the food into a chamber at the upper end of the inclined floor. Gradually, over the many days that the conditioning process went on, the fish learned that food was in the chamber when the temperature of the water increased. As this association became more and more firmly established, the subject fish became conditioned to move up the inclined plane. At the same time, the food chamber was gradually moved upward, day by day, ever farther out of the water. At last the fish learned to go quite out of the water, wriggle into the food chamber, and there wait practically high and dry until food was given, which it then seized sharply, and swam and splashed back to its normal position in the deep part of the tank. There was no mistaking the response. If the fish detected a change of temperature, it went through this remarkable performance; otherwise it did not.

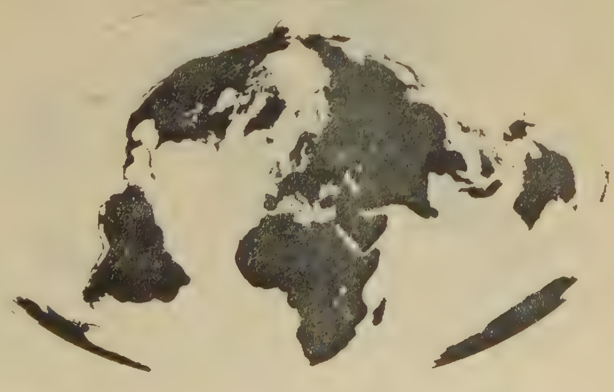
With such experiments, Bull demonstrated that under some circumstances, sea fishes react purposefully to changes in temperature of only 0.03° C., and in salinity of 0.2 parts per thousand. These results indicate the extreme care with which field oceanographic studies must be designed, and the precision with which observations must be made at sea—the figures are close to the limits of accuracy of hydrographic instruments—in order to determine relations between oceanographic conditions and biological effects. They also suggest how some striking changes in marine climate that have been observed in recent years can affect the fish directly. The distribution of marine animals is sharply limited by temperature barriers, as I will illustrate with a few charts:



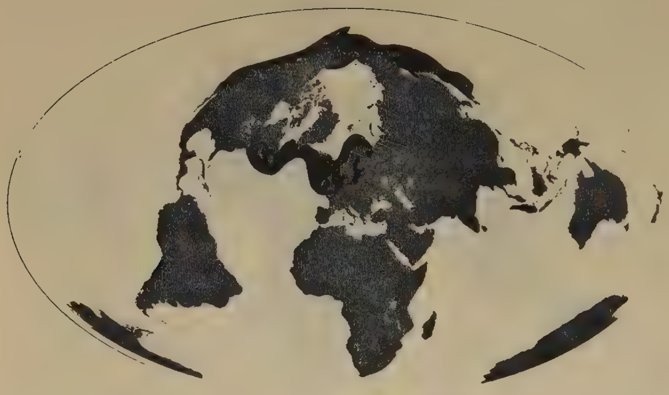
SARDINES (with mean annual surface isotherms)

Figure IV. A chart showing the distribution of sardines of the world. Sardines are somewhat less closely bound to land masses than are other members of the same family with which we are familiar, namely herring, menhaden and shad. Shad must ascend rivers to spawn; menhaden spawn about estuaries; herring in the intertidal areas; sardines may spawn as far as 200 to 300 miles at sea. Their young come close in, the first months of life along shore. The temperature range of sardines (about 12° to 20° C.) is intermediate between that of the menhaden and that of the herring.

Figure V. A chart showing the distribution of menhaden and similar fishes. In general, these require warmer water than pilchard can tolerate and they occur only in regions with extensive estuarine areas. They spawn in or near estuaries, and their young move into salt water sloughs and marshes and even up into fresh water during their early growing period. Thus the growth and survival of menhaden are more affected by local conditions than many other marine fishes. Inshore conditions of the environment are less stable than are those offshore, hence these fishes are more subject to violent fluctuations.

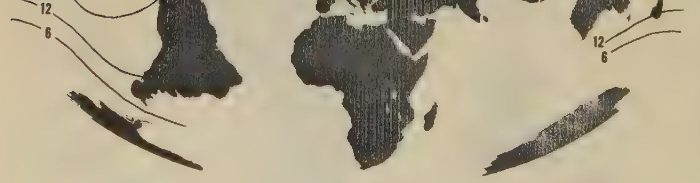


MENHADEN



HERRING

Figure VI. A chart showing the world distribution of herring. This is a cold water fish occurring only in the northern hemisphere, north of the range of pilchard.



PACIFIC SALMON (with mean annual surface isotherms)

Figure VII. A chart showing the distribution of Pacific salmons. This group of fishes can exist only where there is a peculiar combination of stream conditions and of oceanic conditions, as proved by the fact that although their eggs have been transplanted to many parts of the world, Pacific salmon have taken hold only where environmental conditions approximate those of the North Pacific, i.e., New Zealand, Chile, Maine, New Brunswick. In streams, the optimal temperature conditions for the incubation period are somewhere between 4° and 11° C. Eggs suffer severe mortalities if subjected to excessive periods outside those limits. After hatching, the optimal temperature range which controls the growth and survival of the young lies between 13° and 17° C. Prolonged periods beyond these limits cause excessive mortalities among the young. In the ocean, salmon seem to be limited during their spawning and seasonal migrations to a temperature zone at the surface of about 0° to about 20° C.

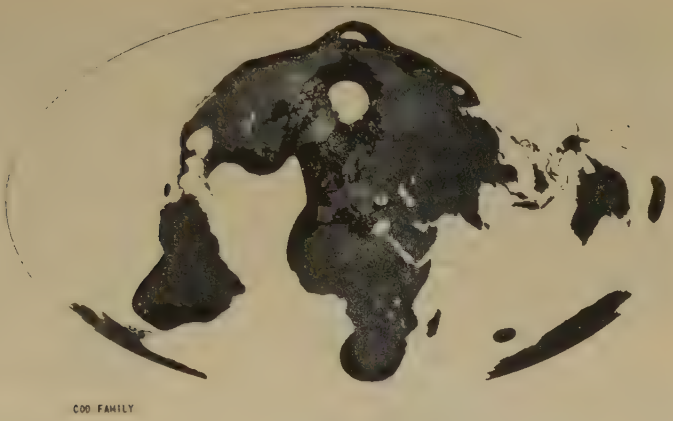


Figure VIII. The cod family which furnishes about 19 percent of the world's harvest of sea fish is widely distributed on continental shelves in temperate latitudes.

I have shown you that various groups of fishes are confined to certain types of environments and in particular to certain temperature zones. Is there any evidence that there could have been important changes in the location of the boundaries of these zones in recent years that might account for changes in accessibility or abundance of the fishes? In places, yes, as the following charts will show:

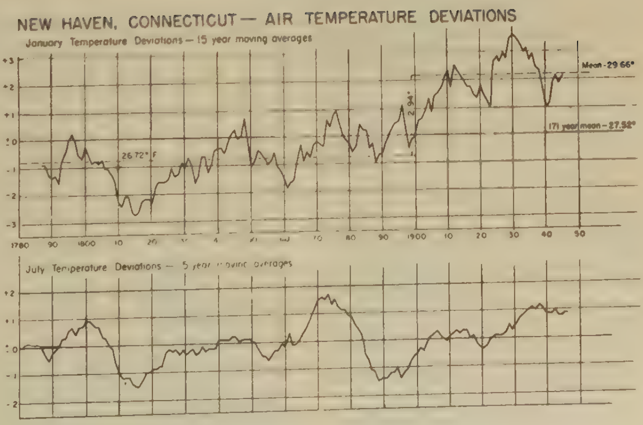


Figure IX. North Atlantic weather as reflected by anomolies in temperature at New Haven. Deviation of average monthly temperature from a 150-year average shows irregular fluctuations and a trend toward warmer winters and summers beginning about 1890 or earlier. Here it has been demonstrated that air temperature and sea surface temperature are positively correlated.

Many European scientists have pointed out evidence that arctic and subarctic areas have been warming, and that there have been pronounced changes in fauna and flora.

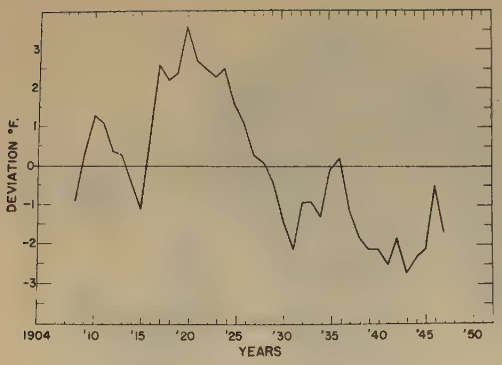
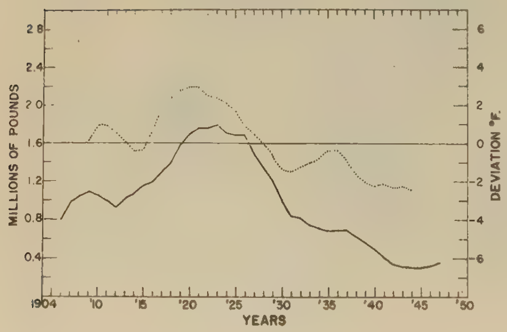


Figure X. The difference between average winter (January) and summer (July) temperatures at the surface of the sea water at Boothbay Harbor, Maine, has decreased since about 1920, indicating an increased mildness of climate. A graph shows annual deviations of these differences from average over the period 1906 to 1947.

Figure XII. Thirty years weather in Rhode Island as indicated by difference between January and July average temperatures. These differences are plotted as deviations from normal. This graph is compared with the commercial catch of lobsters in Rhode Island. This comparison indicates a positive correlation between the catch of lobsters and the degree of difference between January and July temperatures. Rhode Island is near the southern end of the range of lobsters. During a series of years of relatively cold winters in Rhode Island, lobster fishing flourishes; during a series of warm winters, it languishes.



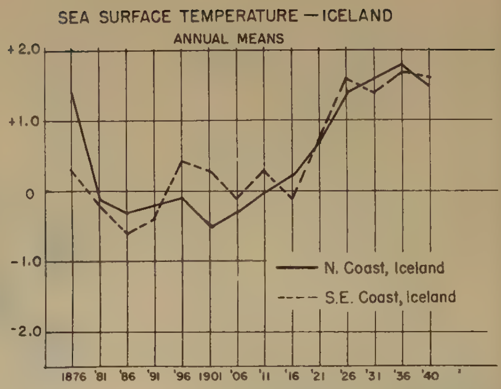
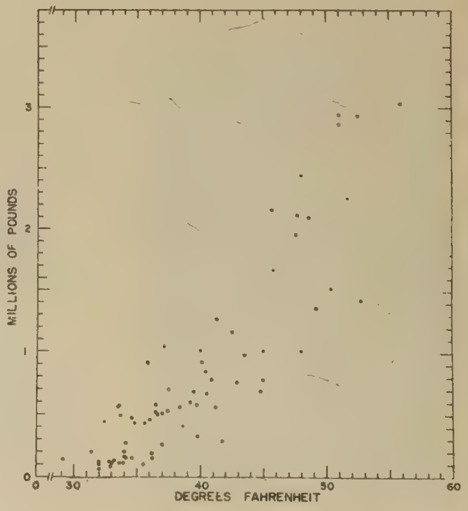


Figure XI. Annual average sea surface temperatures at Iceland have increased during this century, as shown in the following chart.

Figure XIII. The catch of lobsters in Maine, on the other hand, is positively and significantly correlated with the temperature of the surface of the sea water as measured at Boothbay Harbor.

Rhode Island is close to the southern extreme of the geographic range of lobster. The effect of the climatic change was to shift the zone of most favorable conditions toward the north.



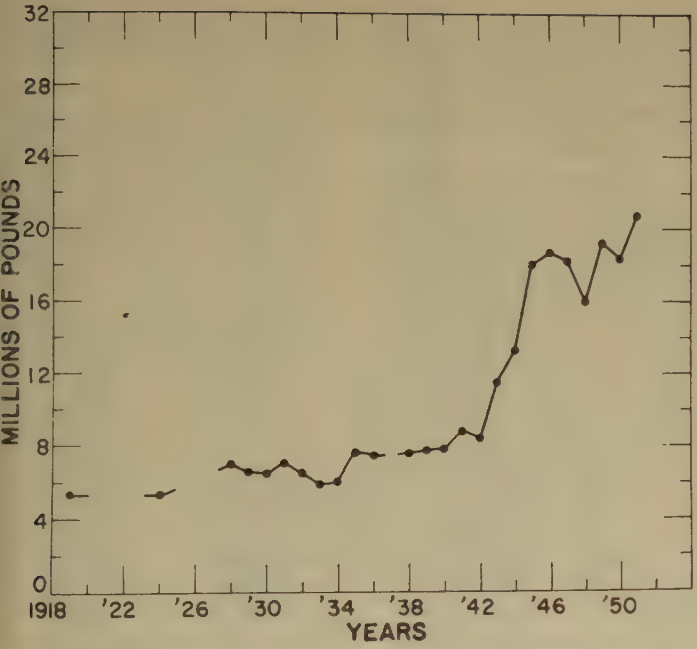


Figure XIV. Commercial catch of lobsters in Maine, 1918-51, shows an increase in catch from 8 million pounds to over 20 million pounds.

There are various ways by which climatic changes of this sort might affect these food fishes. Most directly and simply, they could change the location of the environment having the physical characteristics to which these fishes are physiologically adapted.

If a fish feels uncomfortable because it is too hot, it will move into a cooler zone. This is probably true not only of fishes but of all other classes of animals. Warming encourages invasion by predatory species from warmer zones, and these drive out the former dominating residents. This sort of action may go on all the way along the food chain.

Another effect of changing climate is to stimulate diseases to burst into epidemic proportions. There is mounting evidence that fungi and viruses, which are very sensitive to temperature changes, sometimes severely decimate populations of marine animals and plants.

Striking examples of changing distributions are given by the spread of the mussel parasite and the green crab in the North Atlantic; the northward spread of the cod into the arctic; the return of menhaden to the Gulf of Maine; the shift in composition of the species of shrimps of the Gulf of Mexico, and of shads off the coast of India.

Biologists have been rather slow to become aroused to the possible significance of these changes. Those in countries bordering the Atlantic were first to become interested, perhaps because the effects are more striking in the North Atlantic. Gradually this interest is spreading to other parts of the world, and scientists are beginning to consider the possibility that we are dealing with a world-wide phenomenon.

Fluctuating Fishery Stocks: What We Know about This World-wide Riddle

By Roger Revelle, Director, The Scripps Institution of Oceanography of the University of California

The seas are so vast, and so alien to us as land mammals, that it is difficult for us even to conceive of the ways of life in the ocean. For this reason, we are liable to explain the widespread disasters to the fisheries during the last few years in one of two ways:

We may indulge in self-recrimination and say that the fish populations have become depleted by merciless exploitation. This is the point of view of those who claim that most of the fish are now in a can. Alternatively, we may say that fish are wayward creatures whose behavior is whimsical and irrational. They appear in a certain area for no apparent reason, and they disappear. This point of view may be summarized by the statement that fish, like gold, are where you find them.

There is undoubtedly some truth in both these ideas. But it is my chief purpose today to present a third point of view: that fish, like all other living things, are to a great extent creatures of their environment; the sizes and locations of fish populations depend on the characteristics of the ocean waters in which they live. It follows that we may gain a useful understanding of the fluctuations in the fisheries by achieving a greater understanding of the oceans. This third point of view may be summarized by saying that fish are better oceanographers than people, for at the present time, unfortunately, our knowledge is so fragmentary and our understanding so limited that in many cases we cannot satisfactorily explain what has happened to large fish populations.

To establish a framework for understanding of the ocean waters, it is tempting, though it may be dangerous, to draw analogies between the familiar conditions of life on land and the strange world of the sea.

On land the cycle of plant and animal life appears to us a simple, straightforward one. First there is the grass, which by a subtle and complex chemistry captures the energy of sunlight and builds organic matter. Then there are the deer and the cows that live on the grass, and the tigers and men who eat the deer and the cows.

Part II—Other Contributing Factors; The Green Pastures of the Sea

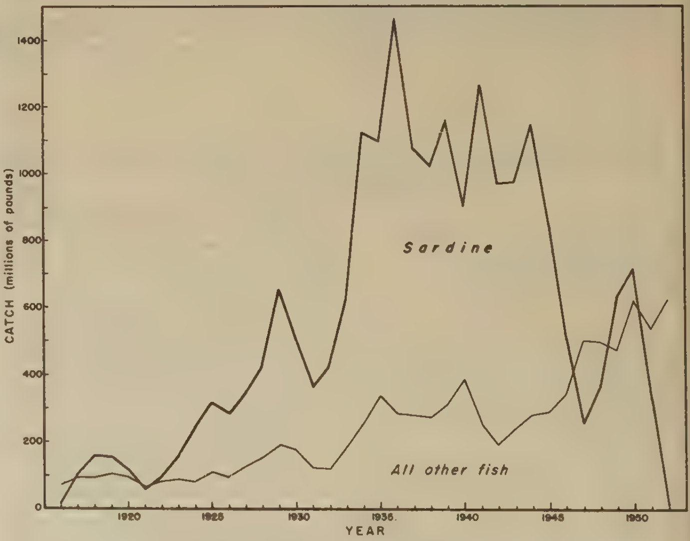
Finally, there are the bacteria which decompose the dead bodies and the excreta of all living creatures, making the constituent substances again available as building materials for the plants. In the sea the same cycle of sunlight, plants, animals and bacteria exists, but with what a difference. Instead of grass there are tiny plants floating in the blue waters, and in place of cows the animals that eat these plants are copepods no bigger than the head of a pin. The tigers that eat the cows are arrow worms and euphausids, only a fraction of an inch in length, and a series of intermediate meat-eaters exists between them and the fish, which represent for us the ocean harvest. Since every link in this long food chain is inefficient, it is not surprising that we reap from the ocean only about 20 million tons of food a year—only a small fraction of the production of our farms on land, and less than a tenth of one percent of the organic production of the sea.

On land, we are used to a great compression of the zone of life. For the most part, it is confined to a thin surface layer a few tens of feet thick. But the whole giant volume of the sea is the theater of life. Even in the great depths seven miles below the surface, where no light penetrates, the temperature is always just above freezing, and the pressure is more than 15,000 pounds per square inch, recent oceanographic expeditions have found scores of different species, and the bottom muds at these depths teem with bacteria. But the plants of the sea, on which all other living things depend, grow only in the waters near the surface where bright sunlight penetrates. These subsurface waters differ widely in fertility. Like the land, the ocean has its green pastures, where life flourishes in abundance, and its deserts where a few poor plants and animals barely survive. Unlike the rich soil of Iowa, which remains nearly constant in fertility from year to year, even the most productive ocean areas sometimes drastically decline in a relatively short time. After a period of years they may with equal abruptness apparently recover their fertility.

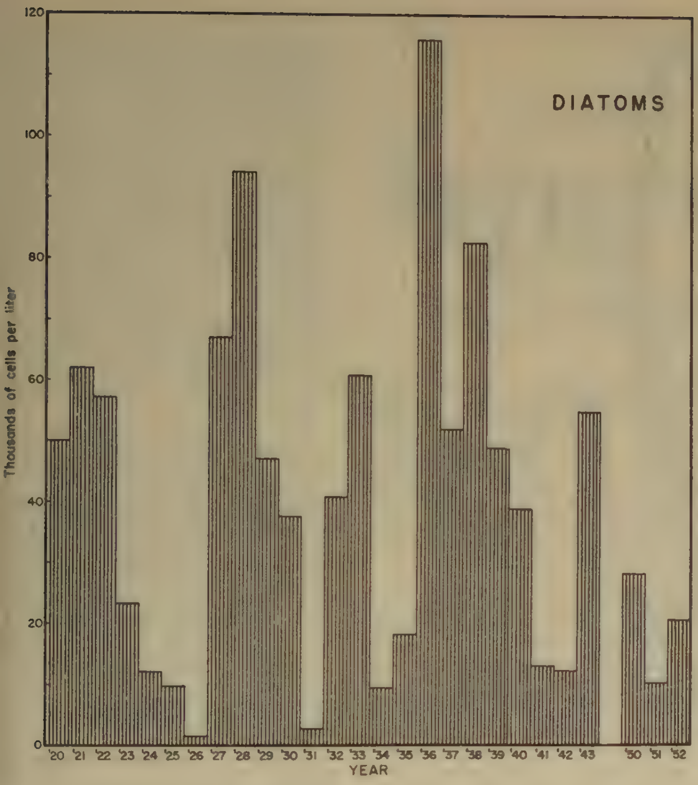
The fertility of the land depends primarily on four things: air temperatures throughout the year; the intensity of sunlight during the growing season; the amount of water; and the presence of a sufficient amount of plant nutrients in the soil—that is, substances such as phosphate and nitrate and many others, which usually occur in very small amounts but are essential for plant growth. We can easily see the importance of all these factors by contrasting the luxuriant growth of a tropical sugar cane field, where the temperatures are warm throughout the year, the rainfall is abundant, and the soil is supplied with plant nutrients by fertilization, with the sparse growth in a dry desert or on the cold Arctic tundra, or on the rocky, glaciated, virtually soilless hills of New England.

In the sea, water is of course always abundant, the plants are well adapted to the relatively narrow range of temperature; and the intensity of sunlight determines the length of the growing season and the depth to which plants can grow, but apparently not the differences in fertility. These depend only on the plant nutrients present in the waters near the surface. As with any well-worked soil on land, these plant nutrients must be replenished each year. They are always being depleted by the slow sinking of plant and animal remains from the brightly lighted subsurface waters into the dark waters of the depths. Men plow the soil to restore its fertility by bringing up to the surface the plant nutrients which have been carried downward in solution. Similarly, the fertility of the sea is restored when the nutrient-rich deep waters are brought up near the surface. This "plowing of the sea" must be carried out on a very large scale and can only be accomplished by the ocean itself. The regions where the ocean plowing is most effective are the green pastures of the sea.

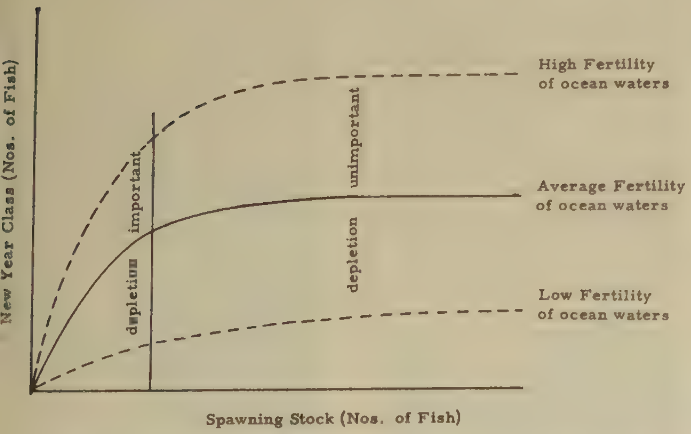
The ocean plowing is accomplished in one of three ways. In some regions the wind drives the surface waters away from the coast, or away from an internal boundary in the sea, and nutrient-rich water wells up from mid-depths. In other areas the surface waters are cooled near to freezing in the wintertime, become heavy and sink, and mix with the nutrient-rich deep waters. Elsewhere, violent turbulence occurs along the boundaries between major ocean currents, and some of the nutrient-rich deep waters are thereby brought into the brightly lighted zone where the nutrients can be used by the plants. As Sverdrup has pointed out, most of the great fisheries of the world depend for their existence on one or another of these three ways in which the ocean plows itself. The sardines, anchovies and mackerel of California, the sardines of South Africa, the tunas off the West Coast of North and South America, the bonitos, albacore and hake of Chile and Peru, the apparently abundant deep tunas in the equatorial zone of the Pacific, all live in regions of up-welling, where the deep water is pumped to the surface by the wind.



1. From 1922 to 1946 The Catch of Pacific Sardines Exceeded in Weight That of All Other California Fisheries Combined. (California Marine Research Committee Annual Report.)



2. Annual Average Numbers of Diatoms in Water Samples Collected at the End of the Scripps Institution Pier from 1920 Through 1952. (California Marine Research Committee Annual Report.)

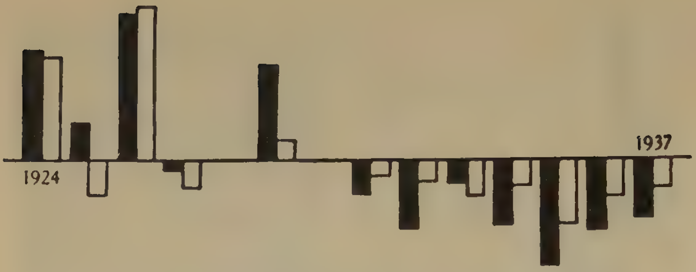


3. Theoretical Curves Relating Numbers of Fish in the Spawning Stock to Numbers of Fish in a New Year Class.

The cod, herring and haddock of Newfoundland, Labrador, Iceland, Greenland, and Bear Island live in the regions of winter cooling. The sardines of Maine and the flat fishes of the Grand Banks live where the Gulf Stream and the Labrador Current clash in turbulent mixing; the sardines and herring of Japan and Kamchatka similarly depend on turbulence between the Oyashio and Kuroshio, which are the west Pacific equivalent of the Labrador Current and the Gulf Stream. All three processes are important around Antarctica, where the giant whales live in such great abundance. The guano industry of Peru, the very life-blood of that land, depends on intense up-welling on the shoreward side of the Peru Current. There the guano birds carry out what is probably the world's largest fishery, amounting to several million tons of anchovies and their relatives each year.

Variations in the weather and in the speed and location of ocean currents, and possibly in the amount of soil and dissolved material carried to the sea by the rivers bring about wide variations in the fertility of the sea's green pastures. We have some evidence for this in the observed fluctuation of the annual crop of plant plankton in different regions. Other evidence comes from fluctuations in the numbers of young fish before they are old enough to be caught by the fishermen. Most fish of the high seas spawn so many eggs that it is difficult to believe these fluctuations in young fish numbers can be due, except in cases of extreme depletion of the spawning population, to fluctuations in the number of adults. Perhaps it is better to say that the variations in the amount of available food and in the numbers of predators and competitors are so great as to mask any relationship between the numbers of adults and the size of a new year class.

Variations in the strength of the new year class, not apparently related to the size of the parent stock, have been observed in many fisheries; for example, the Atlantic, Pacific and Japanese herring, the North Sea plaice, the Atlantic haddock and cod, and the California sardine. In most instances we are not sure whether these are brought about by actual changes in fertility, by some other process related to the ocean circulation, or by little understood biological factors. One instance in which changes in the fertility of the water would appear to be closely related to changes in the young fish population is in the English Channel, where during the years from 1924 to 1937 Russell found good correlation between the winter maximum of phosphate in the water and the numbers of summer-



4. Relationship Between Dissolved Phosphate and Numbers of Young Fish in the English Channel. Black Bars Represent Deviation for each year . . . (After Harvey)

spawned young fish. Fluctuations in the adult population—that is, the rate of natural mortality—may also be related to variations in the food supply—that is, the fertility of the water. The unexpected decline in the catch of Alaska pink salmon in 1953 could well be an example.

Perhaps of greater importance, both to the fish and the fisheries, than the variations in fertility of a particular region, are the fluctuations in the weather and in ocean currents, and the accompanying changes in the temperature and other properties of the water. Just as the elk of the plains and the caribou of the tundra live in a well-defined climatic region and migrate north and south as climates change, so each species of fish has a limited range of tolerance to the ocean climate. Moreover, even though the fish can swim fast and well, their movements seem to be affected by the ocean currents. Consequently, the distribution of a fish population may change as the currents change. But the locations of the areas of high fertility are not much affected by the currents. Thus, both the adults and the young fish may be carried out of regions of high fertility and good food supply into a harsher environment, where many of them must starve or be weakened in vitality so that they become easy victims to predators. There are no fences around the green pastures of the sea. For example, one of the principal factors bringing about recent poor year classes of California sardines may be changes in the ocean currents off the California coast. During the years when the young sardine population was large, a pronounced counter-current flowed northward between the shore and the southward moving California Current. The counter-current has been weak or absent during the last few years, and the center of population of both the adult and young California sardines has shifted southward far down the coast of Lower California. The fertility of this area is probably much less than that of the waters off California, and it is likely that at least some racial groups of the sardine population have greatly diminished in numbers. In the Atlantic, variations of year class strength of plaice, herring and other species have been shown by Jensen to be correlated with fluctuations in the currents between the North Sea and the Baltic.

In addition to their effect on population size, changes in water temperature and ocean currents may profoundly affect the success of a fishery in another way: by making the fish more or less available to the fishermen. From the point of view of the fishermen, we may divide these fluctuations in temperature and currents into two classes: long-term changes and short-term changes. The increase in the cod fishery of Greenland during the last 40 years is a classical example of a beneficial effect of a long-term change in ocean temperature on the fisheries. Here the average water temperature increased by nearly 2° F. during the 20 years from 1906 to 1926, and is still considerably above the average for the middle of the last century. This increase in ocean temperature has been accompanied by a great northward migration of the cod.

Off Southern and Lower California, the average air temperature, and presumably the water temperature, decreased by about 2° F. from 1850 to 1900, and has apparently since slightly increased. Several species of warm-water fishes were abundant off San Diego in the 1850's and have only rarely been seen since that time.

Major changes in ocean currents and ocean temperatures over a short term usually have a bad effect on an established fishery because they result in the movement of the fish out of the area where the fishermen can profitably catch them. In general, the more highly developed and specialized a particular fishery becomes, the more vulnerable it is to changes in fish distribution. For example, the southward move of the sardines from Southern California to Lower California waters has made them virtually unavailable to our California fishermen. Fluctuations in the temperatures of the waters off Japan and presumably in the position of the Kuroshio and Oyashio currents are closely correlated with the success of the Japanese sardine and herring fishery. Interestingly enough, when the sardine fishing is good, the herring fishing is poor, and vice versa. This suggests that when the southward flowing Oyashio Current is displaced to the south along the Japanese Coast, and consequently the water temperature cools, the sardines move south out of the normal fishing grounds but are replaced by the herring coming in from the north.

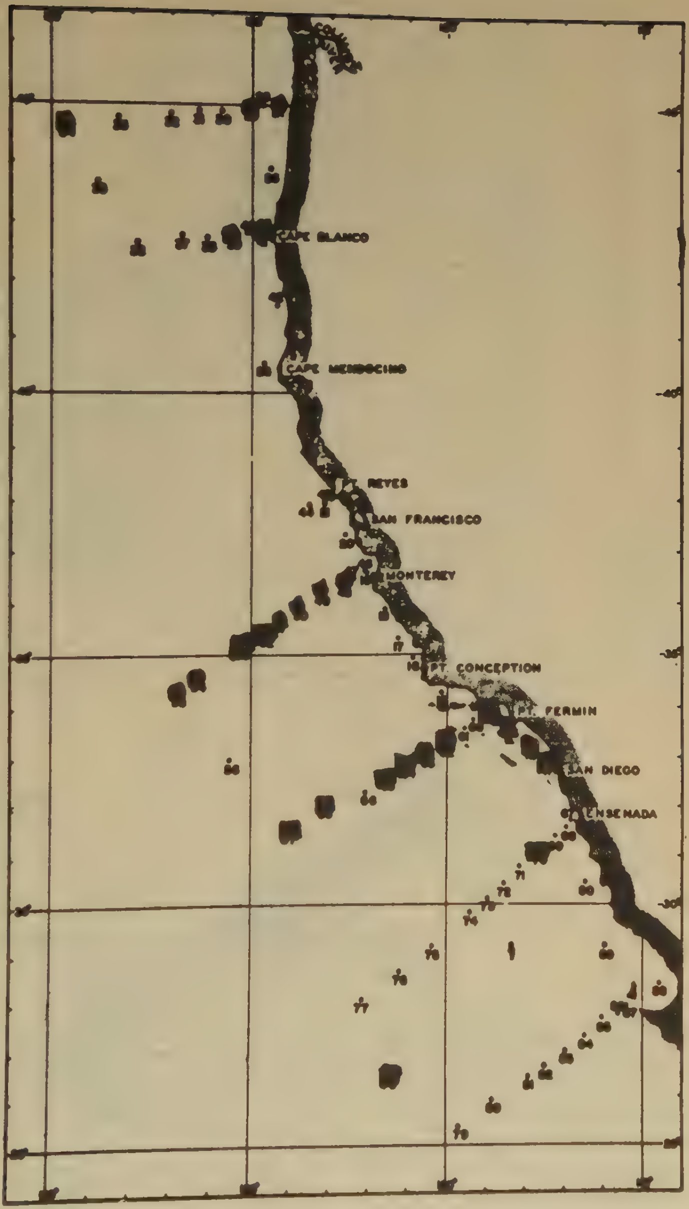
Last year the warm water of the eastward flowing equatorial counter-current turned southward along the coasts of Ecuador and Peru, bringing heavy rains and floods on shore and causing extensive changes in the ocean environment, resulting in mass killings of fish, the deaths of countless thousands of guano birds, and a very sad year for the California tuna fishery. This disastrous shift in the currents occurs, on the average, once every 30 years, and is called él Niño (the child) because it usually happens about at Christmas-time.

It is more than natural to ask whether fluctuations in ocean currents and temperatures can be predicted, for if this were possible, many millions of dollars could be saved by both the fishermen and the processors. Unfortunately, we do not know enough at the present time either about the ocean or the atmosphere to be able to predict changes from year to year.

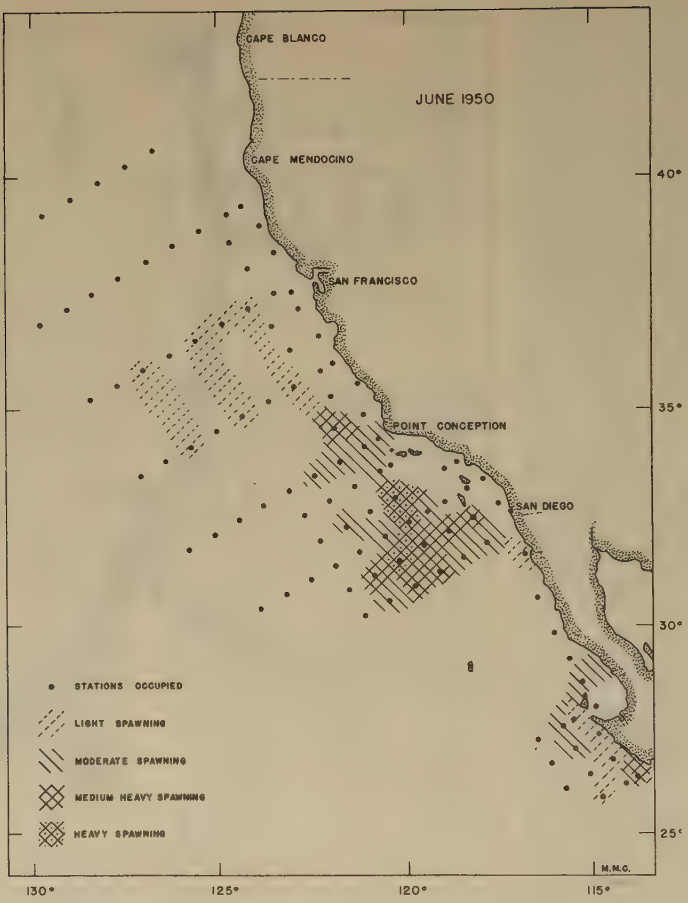
But we can say a few things: first and most important, changes in ocean currents and temperatures do not always go in the same direction, but fluctuate around an average value. Bad luck in the fisheries, even over a period of year, does not spell a message of despair. We have every reason to believe that the situation will sooner or later reverse itself. The question of course is when? Here we are on more uncertain ground, for nearly all the evidence to date suggests that these changes are not cyclical with a regular and predictable period like the tides and seasons, but irregular. We know that change is the natural, not the exceptional, situation. But at present we can predict changes only in a statistical sense. Essentially, this means that large sudden variations are the least likely.

A more meaningful prediction for man requires that we find cause-and-effect relationships, or more accurately, that we discover a series of events that always happen in a certain sequence and are correlated in magnitude. Moreover, predictions are of value only if they can be made a considerable time in advance. This requires that the event on which we base our prediction must happen a considerable time before the event we are trying to predict. Because fish usually take several years to grow up, we have a hope of developing a useful prediction system for variations in the size of populations if what happens to the young fish is important in determining the numbers of adults. On the other hand, in order to predict where the fish will be a year or so in advance, that is, the locations of populations, it will be necessary to find some relationship between the weather and the currents, in which what happens to the weather today will affect the currents several weeks or months, or preferably years from now. We have at least a glimmering of a relationship between world-wide weather phenomena and fluctuations in the ocean currents. In the North Pacific, for example, there is usually an area of atmospheric high pressure. It is possible that when the center of this high pressure area moves eastward, the southward-flowing California current is squeezed against the coast and the counter-current disappears (at least in the surface layer). with the result that the center of sardine population shifts southward out of the range of our fishery. At the same time, the Kuroshio—the Japanese equivalent of the Gulf stream—follows the high pressure area eastward and moves off shore away from the coast of Japan, making room for the Japanese equivalent of the Labrador Current, the Oyashio, to move southward close to shore. The result is that the center of Japanese sardine population likewise moves southward out of the range of the Russian and Japanese fisheries.

It is appropriate here to say a few words about the role of the fisheries biologist and the oceanographer in helping to maintain and develop the fishing industries. At the beginning of this talk I pointed out that we can gain useful understanding of the ways of fishes through greater understanding of the oceans. Science and engineering can be of greatest value in the service of man only if they proceed logically in four steps: from a foundation of careful observation of what is taking place in nature through understanding of why things happen, to prediction of what will take place, and finally to control of nature. This is a long and slow process. Too often in fisheries science we have attempted to run before we could walk—we have established controls and attempted to



5. Oceanic Stations Where Sardine Eggs or Larvae were Found by Ahlstrom in the Spring of 1939. (U. S. Fish and Wildlife Service Publication.)



6. **Numbers of Sardine Eggs and Larvae at Oceanic Stations off California and Lower California in June, 1950. (California Marine Research Committee Annual Report.)**

predict what would happen before we have understood why things had happened, and even before we have observed what has happened. At the present time in oceanography we are still in the stage of observation.

Each of the four steps of scientific and engineering progress may have considerable value to the fishing industries. By observation, we may help to discover new fisheries resources. The deep tunas found by the Pacific Oceanic Fisheries Investigations south of Hawaii, the king crabs of Alaska, and the shrimp off the Atlantic Coast are examples of new resources discovered by observation. If we can gain understanding of why fish populations change, we may be able to estimate the effects of man on the fisheries and thus to establish useful management measures, of value to all. Through understanding based on observation, we may be able to develop means of prediction which will help in industry planning. Finally it is by no means impossible that we shall learn eventually to control some aspects of the ocean. I am thinking here primarily of the possibility of increasing the fertility of the green pastures of the sea. Ten years ago I would have said that this was impossible or at least economically unfeasible. For example, I believed that the fertility of the California waters depended upon the phosphate and nitrate brought up to the lighted zone by up-welling. This amounts, at a minimum, to several hundred thousand tons of phosphate a year. But recent work suggests that the fertility actually depends on substances present in very much smaller concentrations than the phosphate. It may be that the total amount of these substances needed to double the fertility of the California waters each year is only one or two thousand tons, and if so, we might eventually by a relatively small expenditure, be able to add these substances to the water and thereby to increase greatly the yield of the California fisheries.

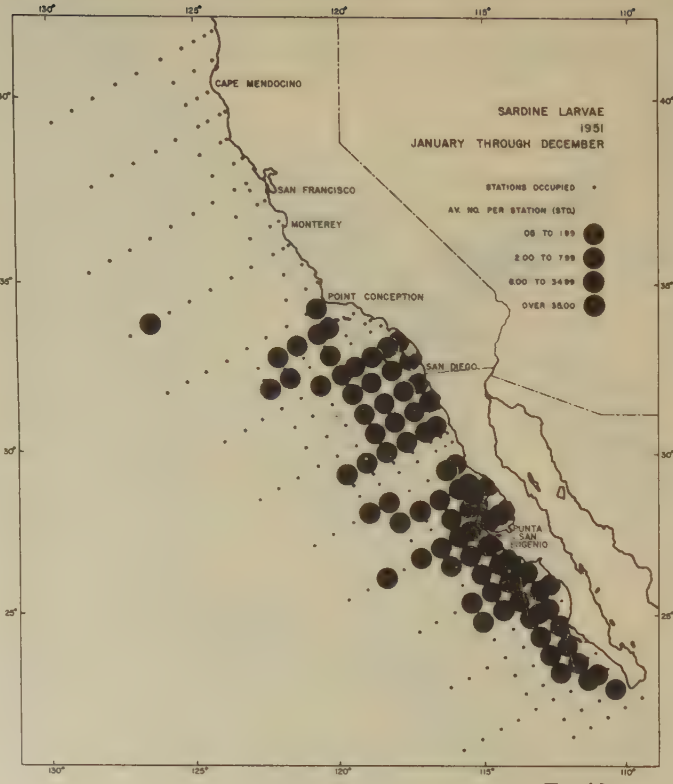
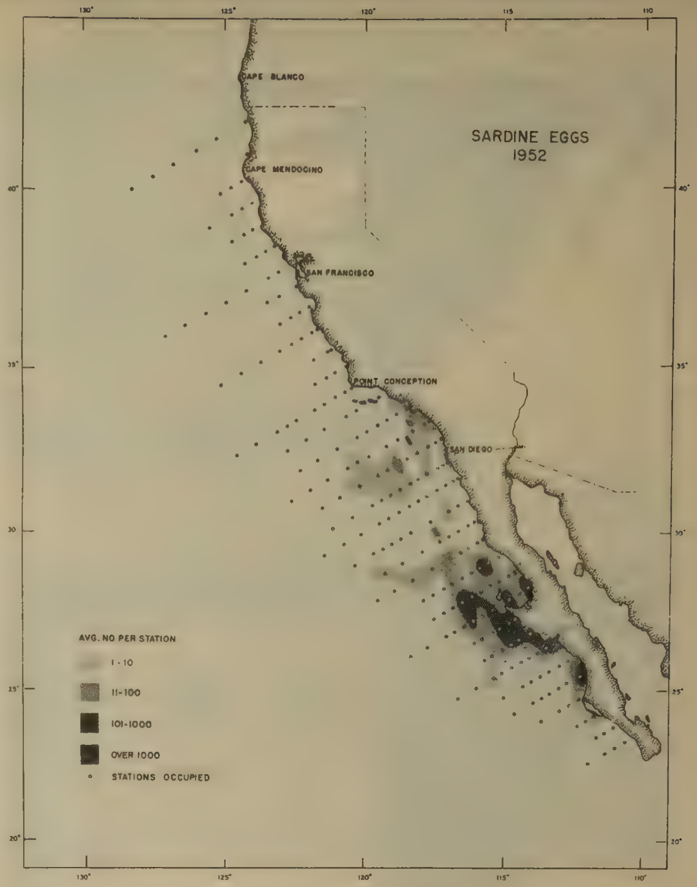
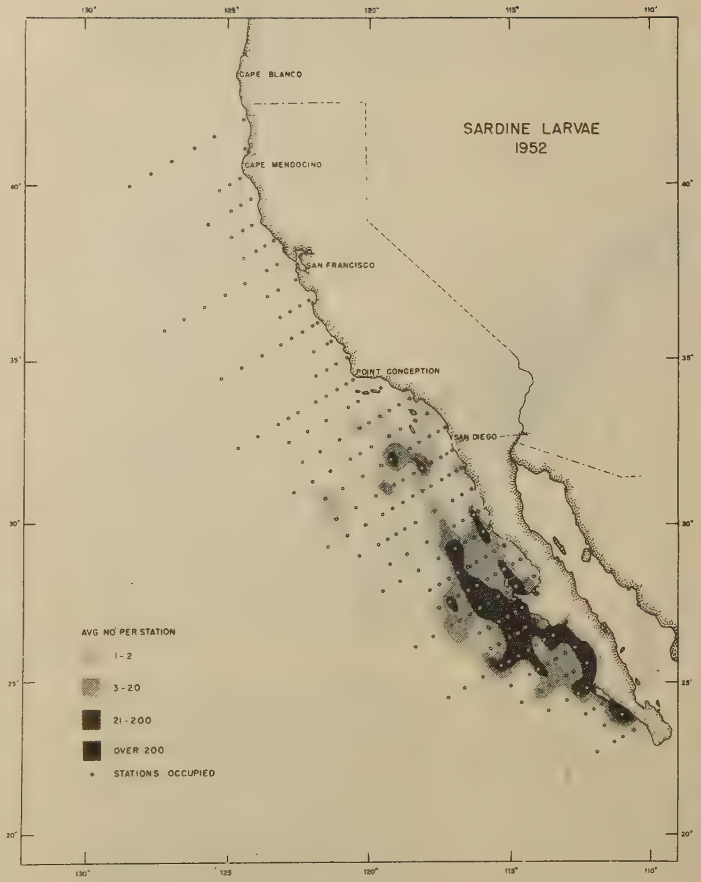

SARDINE LARVAE
1951
JANUARY THROUGH DECEMBER
STATIONS OCCUPIED
AV. NO. PER STATION (STD.)
08 TO 1.99
2.00 TO 7.99
8.00 TO 34.99
OVER 35.00
CAPE MENDOCINO
SAN FRANCISCO
MONTEREY
POINT CONCEPTION
SAN DIEGO
PUNTA SAN EUGENIO
130°
125°
120°
115°
110°
40°
35°
30°
25°

FIG 47

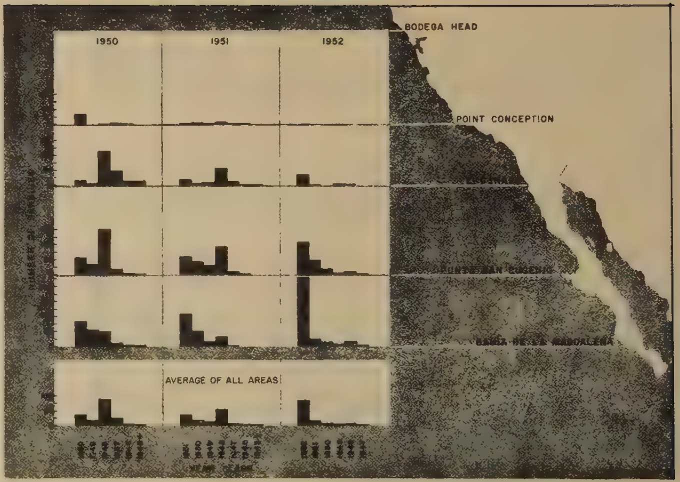
7. Numbers of Sardine Larvae at Oceanic Stations off California and Lower California in 1951. (California Marine Research Committee Annual Report.)


SARDINE EGGS
1952
AVG. NO PER STATION
1 - 10
11-100
101-1000
OVER 1000
STATIONS OCCUPIED
CAPE BLANCO
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO
130°
125°
120°
115°
110°
40°
35°
30°
25°
20°

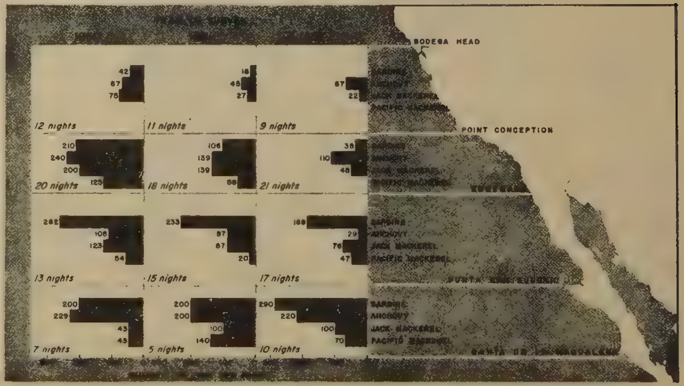
8. Numbers of Sardine Eggs at Oceanic Stations off California and Lower California in 1952. (California Marine Research Committee Annual Report.)


SARDINE LARVAE
1952
CAPE BLANCO
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO
AVG NO PER STATION
1 - 2
3 - 20
21 - 200
OVER 200
STATIONS OCCUPIED
130°
125°
120°
115°
110°
40°
35°
30°
25°
20°

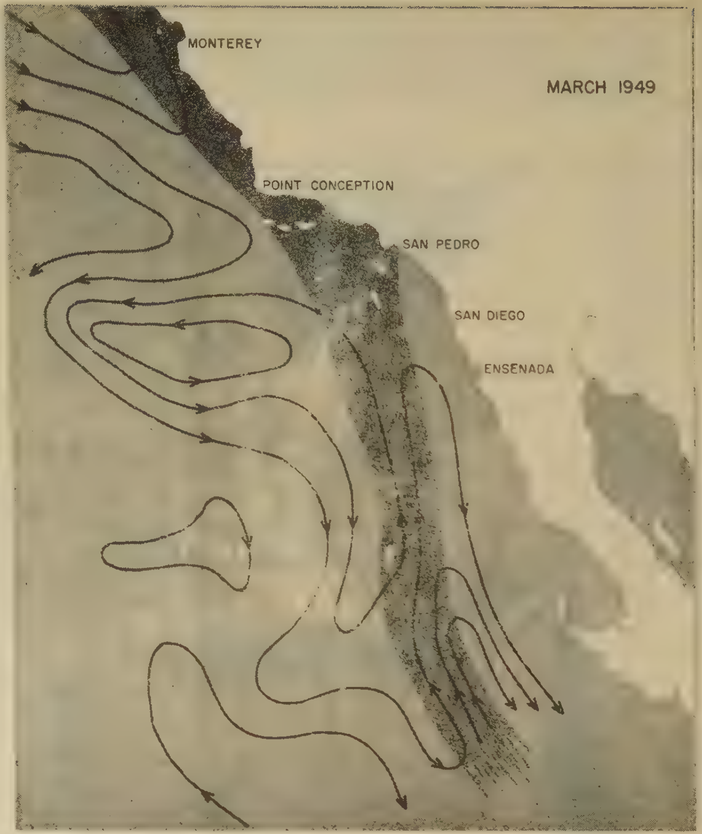
9. Numbers of Sardine Larvae at Oceanic Stations off California and Lower California in 1952. (California Marine Research Committee Annual Report.)



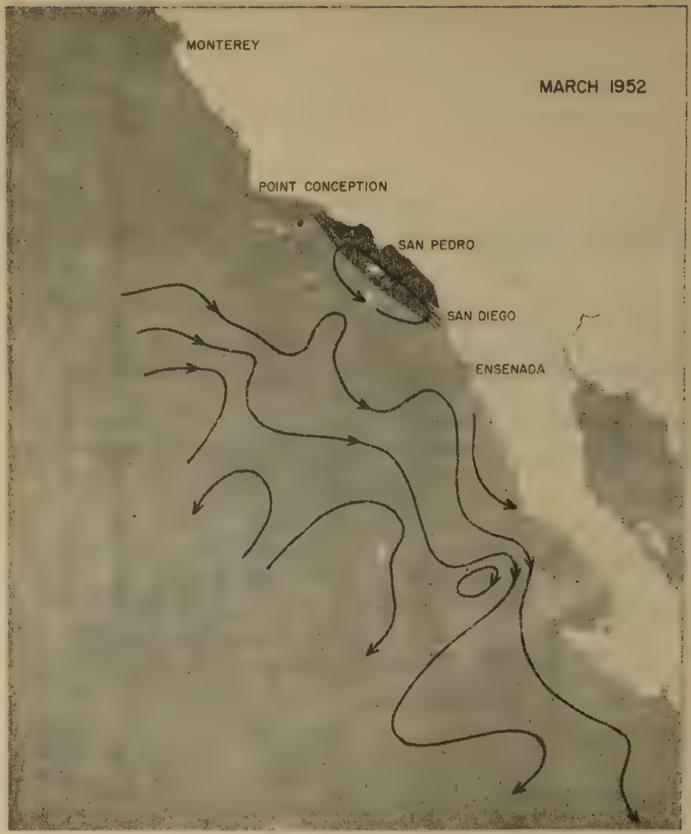
10. Comparative Numbers of Sardines of Different Ages Collected in "Young Fish Surveys" off California and Lower California During the Three Years 1950 Through 1952. (California Marine Research Committee Annual Report.)



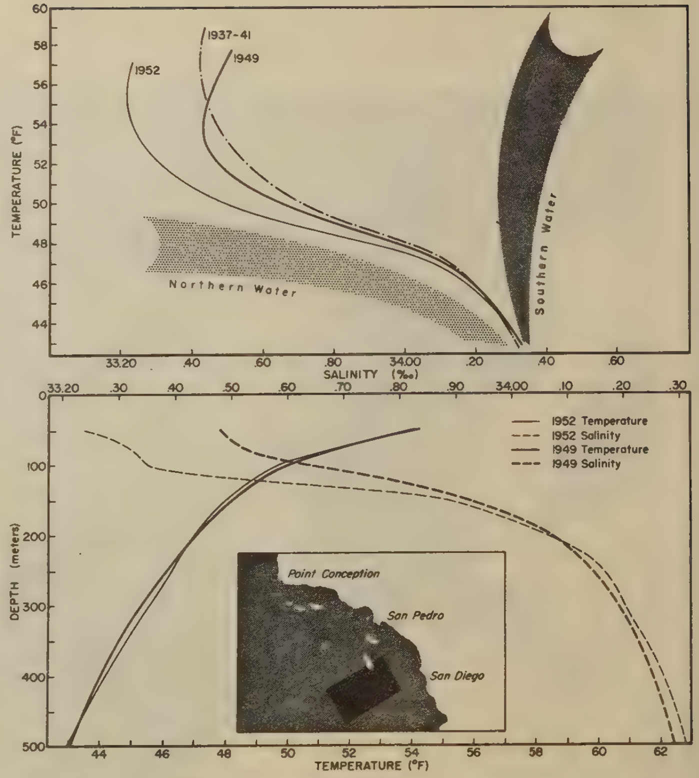
11. Comparative Numbers of Sardines, Anchovies, Jack Mackerel, and Pacific Mackerel Collected in "Young Fish Survey" off California and Lower California During the Three Years 1950 Through 1952. (California Marine Research Committee Annual Report.)


MONTEREY
MARCH 1949
POINT CONCEPTION
SAN PEDRO
SAN DIEGO
ENSENADA

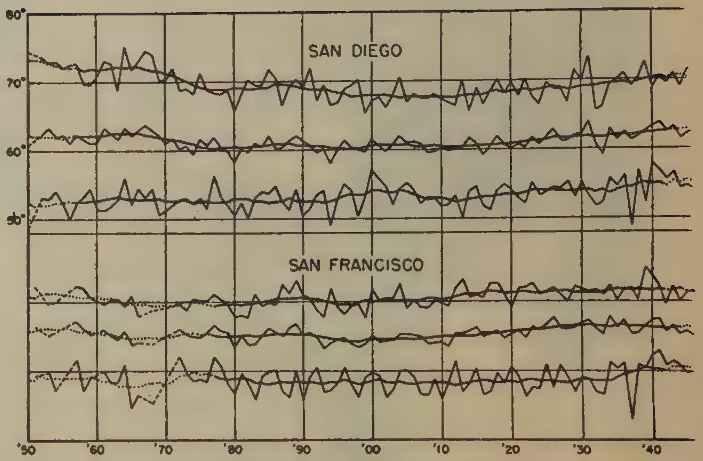
12. In 1949 The Northward Flowing California Countercurrent (Shown by Shaded Area) Was Strong and Broad. (California Marine Research Committee Annual Report.)


MONTEREY
MARCH 1952
POINT CONCEPTION
SAN PEDRO
SAN DIEGO
ENSENADA

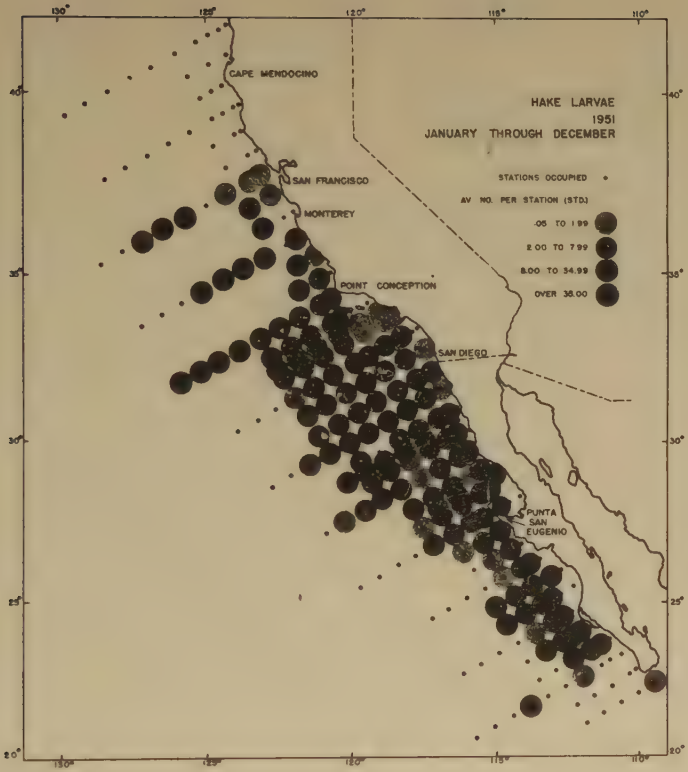
13. In 1952 the Northward Flowing Water was Found Only Inshore in the Southern California Region. Everywhere Else off California and Baja California the Water Flowed Southward. (California Marine Research Committee Annual Report.)



14. The Correlation Between Temperature and Salinity Shows That in 1949 When There was a Relatively Good Sardine Catch, Considerable Water from the South was Present off Southern California Just as in the Very Good Years Between 1937 and 1941. (California Marine Research Committee Annual Report.)



15. 95-Year Records of Air Temperature at San Diego and San Francisco from 1850 to 1945. The Upper Curves Represent the Warmest Month of the Year .... (After Hubbs, 1949)


HAKE LARVAE
1951
JANUARY THROUGH DECEMBER
STATIONS OCCUPIED •
AV. NO. PER STATION (STD.)
.05 TO 1.99
2.00 TO 7.99
8.00 TO 34.99
OVER 35.00
CAPE MENDOCINO
SAN FRANCISCO
MONTEREY
POINT CONCEPTION
SAN DIEGO
PUNTA SAN EUGENIO
130°
125°
120°
115°
110°
40°
35°
30°
25°
20°

16. Numbers of Hake Larvae at Oceanic Stations off California and Lower California. (California Marine Research Committee Annual Report.)

Contributions from Scripps Institution of Oceanography, New Series, No. 704.

Reprinted from COPEIA, 1954, No. 3, July 29, pp. 234-236.

AN ERRONEOUS RECORD OF THE CALIFORNIA KILLIFISH, *FUNDULUS PARVIPINNIS*, FROM CABO SAN LUCAS, BAJA CALIFORNIA[1].—For the nine reasons here detailed, we regard as erroneous the record of the California killifish, *Fundulus parvipinnis* Girard, from Cabo San Lucas at the tip of Baja California, just within the tropics. The record was introduced by Jordan and Gilbert (1882, Proc. U. S. Nat. Mus., 5 (1883): 355) in their list of species recorded in the United States National Museum as having been collected by John Xántus (János Xántus) at Cape San Lucas.

(1) As Jordan and Gilbert pointed out, there had been considerable confusion regarding this collection. The specimens had become scattered and many had been lost or destroyed. The Xántus material was entered in the National Museum catalog at several different times and places. For some of the lots, no original entry was made for locality or for species. The original entry for the specimens in question gave only the locality (Cape San Lucas). Subsequently, in handwriting believed to be that of David Starr Jordan, the name of the species and the collector (Xántus) were added, and under the column headed "Remarks", "(Jordan)" was entered. (We thank E. A. Lachner for this information.) Although there is no good reason to doubt that Xántus collected nearly all of the material accredited to him, doubts have arisen regarding the provenance of specimens from different regions, for example Cabo San Lucas and Colima. Most of the material was probably rightly attributed to Cape San Lucas, but some came from other regions, even from the Atlantic Coast.

(2) The three other species of cyprinodonts reported by Jordan and Gilbert as having been collected by Xántus from the same locality almost certainly came from elsewhere. Thus, the type material of *Ilyodon furcidens*, a goodeid, was very probably collected by Xántus in the state of Colima on the Mexican mainland (Hubbs and Turner, 1939, Misc. Publ. Mus. Zool. Univ. Mich., No. 42: 59), where Xántus operated in 1863 (Kellogg, 1932, U. S. Nat. Mus., Bull. 160: 7; Madden, 1949, Xántus, Hungarian Naturalist in the Pioneer West. Books of the West, Palo Alto [Calif.]: 172–4). The types of *Fundulus vinctus* and *F. extensus* were apparently based on specimens of the common Atlantic Coast species, *F. heteroclitus* (Linnaeus) and *F. diaphanus* (LeSueur), respectively, that had somehow become mixed with the Xántus collection (Hubbs, 1931, Occ. Pap. Mus. Zool. Univ. Mich., No. 231: 2–3). "The false ascription is probably not attributable to Xántus" (Madden, 1949: 275).

(3) No cyprinodonts were reported by Gill (1862–63, Proc. Acad. Nat. Sci. Phila., 1862: 140–51, 242–6, 249–62; 1863: 80–8; and a few subsequent papers) in his descriptions of the extensive material sent to the Smithsonian Institution from Cabo San Lucas. While he was preparing his catalogue of the fishes obtained by Xántus at this locality, Gill was in contact with the collector (Madden, 1949: 162).

(4) There appears to be no suitable habitat for *Fundulus* at Cabo San Lucas (Hubbs has observed the entire shoreline of southern Baja California from the air). Locality records of a century ago, however, were loose, and the small lagoon at the mouth of Río San José, at San José del Cabo, which Xántus visited, might have harbored native cyprinodonts. But none was obtained here among the fishes collected by Gustav Eisen (Rutter, 1896, Proc. Calif. Acad. Sci., ser. 2, Vol. 6: 263–6) or by the ALBATROSS (Osburn and Nichols, 1916, Bull. Amer. Mus. Nat. Hist., 25: 158, 164–5, 175, 180). Nor have any been included in the recent unreported collections known to us to have been made in Río San José or its mouth. All the cyprinodonts obtained recently in that stream are referable to *Gambusia affinis affinis* (Baird and Girard), which was introduced here for mosquito control by Percy S. Barnhart on April 26, 1931 (data from Barnhart's diary, in Scripps Institution of Oceanography).

(5) The Cape fauna is almost strictly tropical, whereas *Fundulus* is essentially a temperate genus. This argument is weakened by the fact that the genus occurs in the probably equally warm waters around the peninsula of Yucatán. The Yucatán species, however, may be regarded as a spillover from the abundant *Fundulus* fauna of eastern North America.

(6) The specimens in question (USNM No. 7242), 6 mature males and 3 mature females, kindly loaned by Leonard P. Schultz, differ in several diagnostic characters from the subspecies, *Fundulus parvipinnis brevis*, described by Osburn and Nichols from Magdalena Bay, Baja California (the southernmost verified outpost of the species and of the genus on the Pacific Coast). And, as noted by Jordan and Gilbert (1882: 355), they are the counterparts of breeding adults of *F. p. parvipinnis* from San Diego Bay, California (the type locality of the species). They agree in the relatively large size of the adults (males 38–52 mm. in standard length, females 53–60 mm. long), in the sooty color of the breeding males, and in the marked elongation of the males' anal rays (longest ray about 2.7–2.9 in standard

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[1] Contributions from the Museum of Zoology, University of Michigan, and from the Scripps Institution of Oceanography, New Series, No. 705.

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TABLE I

NUMBER OF LATERAL SCALES AND VERTEBRAE IN TWO SUBSPECIES OF *Fundulus parvipinnis*

Subspecies	Lateral scales							No.	Ave.
	31	32	33	34	35	36	37		
F. p. parvipinnis									
Carpinteria to Ensenada*	..	..	5	64	184	28	2	283	34.9
San Diego Bay†	..	..	..	19	23	..	..	42	34.5
"Cape San Lucas"	..	..	..	4	5	..	..	9	34.5
F. p. brevis									
Magdalena Bay‡	2	23	23	1	..	..	..	49	32.5

Subspecies	Vertebrae						No.	Ave.
	32	33	34	35	36	37		
F. p. parvipinnis								
Escondido Cr. to Ensenada*	..	..	..	7	12	1	20	35.7
San Diego Bay	..	..	..	1	9	..	10	35.9
"Cape San Lucas"	..	..	1	2	6	..	9	35.5
F. p. brevis								
Magdalena Bay	1	1	8	..	..	..	10	33.7

* Exclusive of San Diego Bay.

† including a cotype, USNM No. 938.

‡ Including holotype, USNM No. 87542 (formerly Amer. Mus. Nat. Hist. 5208), 9 paratypes and 39 topotypes (USNM 125353, UMMZ 157687).

length). They also agree in the high number of lateral-line scales and of vertebrae (Table I). The scale count (from upper end of gill opening to caudal base) is questionable in about half of the specimens, since many scales have been rubbed off. But the minimal rather than maximal number is recorded, and the increased number (compared with that in *F. p. brevis*) is supported by the vertebral counts (taken from X-ray photographs, the urostyle included). The Xántus specimens further agree with topotypes of *F. p. parvipinnis* in the slender body and small head: the greatest body depth enters the standard length approximately 3.7 to 4.1 times; the length of the head enters this length about 3.25 to 3.55 times (we give only approximate measurements, since the specimens are soft and flabby, but we have used care to avoid subjective errors). These data are in close agreement with measurements given by Osburn and Nichols (1916: 151) for San Diego material, and contrast with their data for *F. p. brevis* (body depth, 3.1 to 3.6, and head length, 3.0 to 3.3, in the standard length). The reduced number of vertebrae and scales and the large head and the robust body of *F. p. brevis* are characters that one would expect to find in the southernmost populations of the species.

(7) When Xántus made his collections, from 1857 to 1864 (Madden, 1949), there was a northward shift of the fish fauna in southern California (Hubbs, 1949, Jour. Marine Res., 7 (1948): 459–82) and very probably also in Baja California—minimizing the chance that a temperate species occurred then within the tropics.

(8) Xántus could well have secured the specimens in southern California. He was at San Pedro in April or May, 1857 (Madden, 1949: 55), and was probably in contact with Dr. George Hammond who collected about San Diego (Madden, 1949: 73–4). He shipped a keg of alcoholic specimens to Washington in November, 1857 (Madden, 1949: 89). He may have bought the specimens (he often made such purchases) and then may have mislabeled them as from Lower California, as he is known to have done for a number of birds (Madden, 1949: 129–30), or he may have left them unlabeled. Or, these fish may have become mixed through curatorial mishandling with the Xántus collection from the Cape.

(9) Lastly, it is noteworthy that the erratic Hungarian who is recorded as the collector of *Fundulus parvipinnis* at Cabo San Lucas has been proved in a recent critical biography (Madden, 1949) to have been rather deficient in the virtues of reliability and veracity.—ROBERT RUSH MILLER AND CARL L. HUBBS, *Museum of Zoology, University of Michigan, Ann Arbor, Michigan, and Scripps Institution of Oceanography, University of California, La Jolla, California.*

Deep-Sea Research, 1954, Vol. 1, pp. 216 to 223. Pergamon Press Ltd., London.

Distribution and abundance of the diatom *Ethmodiscus rex* off the west coast of North America*

J. L. McHugh[†]

Summary—*Ethmodiscus rex*, though not present in great numbers, is a common constituent of the plankton throughout the year off the California and Lower California coasts. It has been collected in plankton hauls from 46° 15′ to 23° 45′ N. Lat., and from within a few yards of shore to 400 miles off the coast. The cells are rather variable in size and shape, and reach a maximum diameter of almost 2 mm. The species appears to be most abundant in the offshore waters. Its occurrence as an important constituent of deep-sea deposits in the western Pacific Ocean may be a consequence of its widespread distribution in the plankton.

INTRODUCTION

Recent studies of deep-sea bottom deposits in the tropical Pacific Ocean (Hanzawa, 1933 ; Wiseman and Hendey, 1953) have shown that skeletons and fragments of *Ethmodiscus rex* (Rattray) Hendey often are the dominant constituent. Wiseman and Hendey (1953) were at a loss to account for this phenomenon, stating that the species has been found very seldom in the living state in plankton samples, and concluding that the vegetative season may be short, and that the species probably multiplies suddenly in enormous numbers. A bottom sample taken at 11° 20′N. Lat., 142° 19′E. Long., five miles from the greatest known oceanic depth, was dominated by *E. rex*, yet the diatom was not found in the plankton in this region.

Cupp (1943) did not list *Ethmodiscus rex* from the waters off the west coast of North America, although she and others examined many thousands of samples. Recent studies, however, have shown that the species is not uncommon in the waters off California and Lower California. The first record of *E. rex* in these waters was at Melpomene Cove, Guadalupe Island, in December 1946, when a single cell was taken in a vertical haul with a small plankton net. During Cruise 50 of the *E. W. Scripps*, 30 stations were occupied off the coast of Lower California (Fig. 1). At each, an oblique haul was made with a plankton net one metre in diameter at the mouth, constructed of cottom scrim with mesh openings of 0·80 to 0·95 mm. (Ahlstrom, 1948). The duration of each haul was approximately 20 minutes, during which the net moved forward and upward from a depth of approximately 70 metres to the surface. Of these 30 samples, 15 contained one or more specimens of *E. rex*. The volume of water filtered during each haul, usually about 500 cubic metres or more, was measured with a current meter suspended in the mouth of the net, and the hauls were standardized in terms of the numbers of organisms under 10 square metres of sea surface. On this cruise, the greatest number of cells of *E. rex* per standard haul (74 cells) was at station 5 (29° 38′N. Lat., 119° 19′W. Long.).

When the cruises of the California Co-operative Sardine Research Programme (now the California Co-operative Oceanic Fisheries Investigations) began in 1949, plankton hauls similar to those described above were made at each station. The

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* Contributions from the Scripps Institution of Oceanography, New Series, No. 706.

[†] Formerly with Scripps Institution of Oceanography.

Reproduced, by permission, from Deep-Sea Research, v. 1, 1954.

methods by which the hauls were made are described in more detail by Ahlstrom (1948, 1952). The first operation in examining the samples was to remove all fish eggs and larvae from the entire sample, or from a large aliquot part. Through the courtesy of Dr. Elbert H. Ahlstrom, in charge of this phase of the programme, the technicians were instructed to record the occurrence of *Ethmodiscus* as they sorted the samples. No checks were made on the accuracy of these counts, but because the species is distinctive in size and shape it is unlikely that errors of identity were made. It is considered likely, however, that the various technicians varied in their interest, and in their ability to see the diatom when their attention was concentrated on the eggs and larvae of fishes. For this reason, these counts are not listed here, although they have been used as the basis for general remarks on geographic and seasonal distribution. The distribution pattern of *E. rex* during Cruise 50 of the *E. W. Scripps*, based on counts made by the author, is so similar to the distributions deduced for these other cruises, however, that considerable confidence can be placed in the relative reliability of these data.

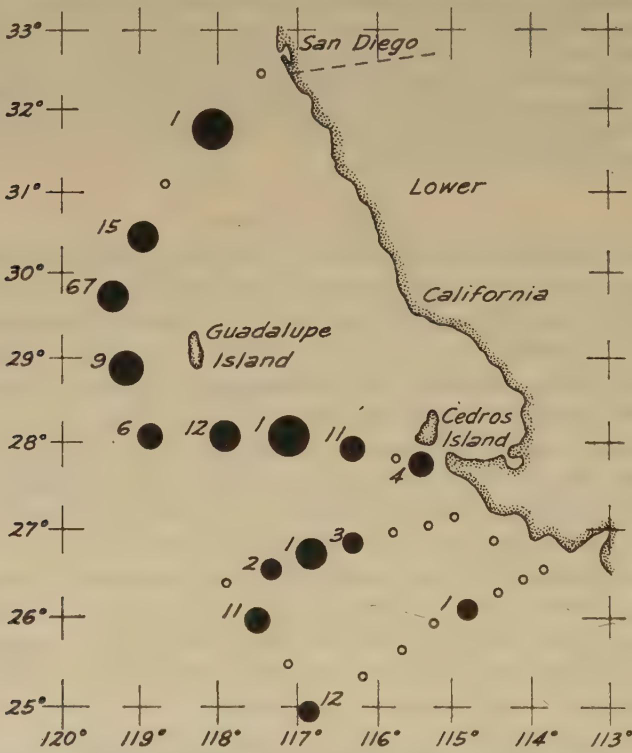

Fig. 1. Station pattern of Cruise 50 of the *E. W. Scripps*, February 1948, showing the numbers of *Ethmodiscus rex* and the relative average size of the cells taken at each station. The diameters of the black circles are proportional to the average valve diameters of the cells ; the number of cells is indicated opposite each circle ; the small open circles are stations at which no *Ethmodiscus* were found.

GEOGRAPHIC DISTRIBUTION

The known geographic range of *Ethmodiscus rex* off the west coast of North America extends from the Washington coast to the coast of Lower California (46° 15′N. Lat.

23° 45′N. Lat.). This coincides with the region covered by the cruises from which *Ethmodiscus* counts are available, namely, Cruises 22 and 50 of the *E. W. Scripps* and Cruises 1 to 7 and 11 to 14 inclusive, of the California Co-operative Sardine Research Programme. Undoubtedly, when the areas to the north and south are investigated, it will be shown that the present known limits (Fig. 2) do not represent the extreme limits of the species range. For example, *Ethmodiscus zodiacus* has been reported from the coastal waters of British Columbia (Bailey and McKay, 1916), and it is possible that this record was based on *E. rex*. In an east-west direction also, the known distribution of *E. rex* in the plankton coincides with the bounds of the survey area. Thus the species has been taken at stations from within a few yards of shore to 400 nautical miles seaward.

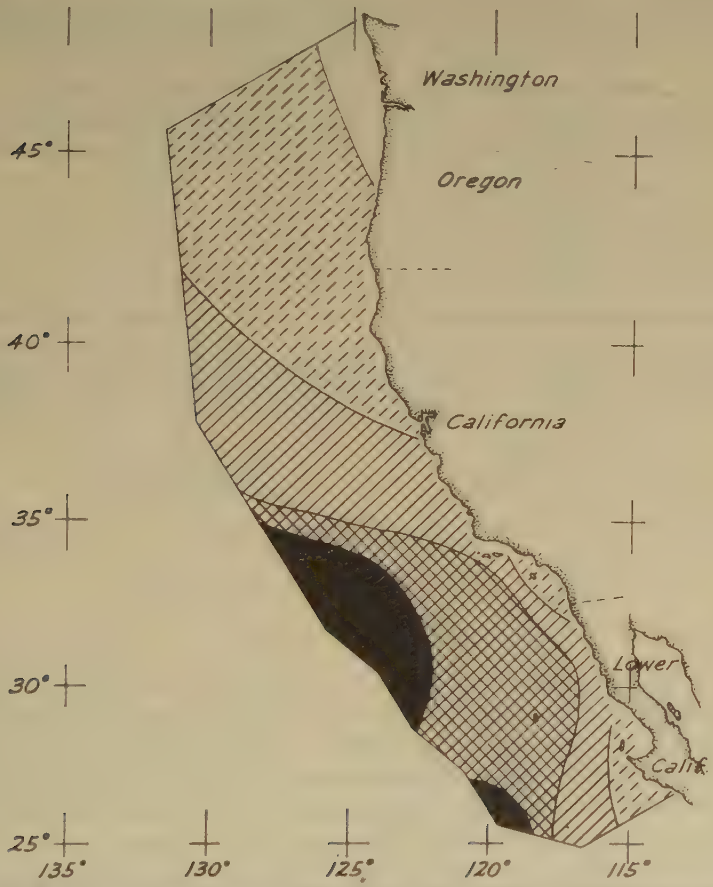

Fig. 2. Relative density of *Ethmodiscus rex* off the west coast of North America as observed on Cruise 50 of the *E. W. Scripps* and Cruises 1 to 7 and 11 to 14 inclusive of the California Co-operative Sardine Research Programme. The density of diatoms is proportional to the density of shading. Absolute values are not indicated because the true magnitude of such values is lost in the averaging process. The original standardized counts, however, ranged from zero (most frequent in the inshore zone to the north) to more than 100 (most common in the offshore zone to the south).

The orginal data, too unwieldy to present in detail, are summarized in Tables I and II. To reduce the number of observations to convenient form, the area was divided into 21 blocks, 3 blocks east to west, and 7 north to south, by lines running roughly parallel and at right angles to the coast. These blocks were numbered 1 to 7 from north to south, and *A* to *C* from east to west. All available observations made within each block were averaged. These averages demonstrate numerically, as Fig. 2 illustrates graphically, that *Ethmodiscus* was more abundant offshore, and toward the south, in the area from Point Conception south to the vicinity of Guadalupe Island, and westward to the offshore boundary of the survey area. Off the Washington coast the species occurred only occasionally, and many hauls contained no cells ; off central Lower California it was less abundant than immediately to the northward, but still was present in most hauls, and occasionally was fairly abundant.

Table I. Relative abundance of Ethmodiscus rex from north to south, expressed as the percentage of standard hauls in each area containing 20 cells or more.

Block number	*Approximate latitude of centre of area*	*Percentage of hauls containing 20 cells or more*	*Number of hauls*
1A-1C	45° 00′N	0	59
2A-2C	41° 30′N	1	98
3A-3C	38° 00′N	9	200
4A-4C	34° 30′N	21	173
5A-5C	31° 00′N	19	272
6A-6C	28° 00′N	18	230
7A-7C	24° 30′N	8	97

Table II. Relative abundance of Ethmodiscus rex from east to west, expressed as the percentage of standard hauls in each area containing 20 cells or more.

Block number	*Approximate distance in miles from shore to centre of area*	*Percentage of hauls containing 20 cells or more*	*Number of hauls*
1A-7A	40	3	174
1B-7B	125	16	563
1C-7C	300	18	392

In an east-west direction abundance was least near the coast, and the frequency of occurrence increased steadily with distance offshore. It would appear that this is a typically oceanic species.

SEASONAL DISTRIBUTION

There is no evidence that the abundance or the pattern of distribution of *E. rex* varies regularly with the seasons in the area studied. Data are available for all months of the year except October and November, and charts showing the distribution for each of the 12 cruises are remarkably similar in their general features. It seems likely that when the distribution in October and November is known it will prove to be similar to the average pattern for the ten months covered by the surveys (Fig. 2).

ABUNDANCE

Records of the number of individuals of *Ethmodiscus rex* under 10 square metres of sea surface are available for 1,129 plankton hauls. Of these, 402 contained no cells, and 727 contained numbers ranging from 1 to 176. Most of the blank hauls occurred off the Washington and Oregon coasts, and it was unusual in any month to find no cells off California and Lower California except in the waters near the coast of Lower California, south of Cedros Island. Since the hauls were made primarily to collect fish eggs and larvae, they seldom exceeded 70 metres in depth. It is possible that, especially in clear oceanic water, the nets did not reach the lower limit of the photosynthetic zone, and thus the hauls were not strictly representative of the entire population. Errors would be introduced also by failure of the net to retain the smaller cells.

VARIATIONS IN SIZE AND SHAPE

Ethmodiscus rex and some of its close relatives are the largest diatoms known. Hendey (Wiseman and Hendey, 1953), in the only satisfactory description of *E. rex* available, states that the valve diameter ranges from 1·7 to 1·9 mm.

Measurements of 156 specimens from *E. W. Scripps* Cruise 50 show that in waters off the Lower California coast the size is much more variable. In this material the valve diameter ranged from 0·34 to 1·81 mm, the pervalvar axis from 0·32 to 1·36 mm, and the girdle width from 0·21 to 1·13 mm. The size of the smallest cells may have been determined by the mesh size of the net. The shape of the valves showed extreme variation also, from relatively long cells with convex valve mantles, to squat pillbox-like structures with one or both valve mantles flat. Some of the many variations in size and shape are illustrated in girdle view in Fig. 3. A slight concavity often is present in the centre of the valve. This apparently represents the surface of attachment of recently-divided cells, a pair of which is shown at the upper left in the figure.

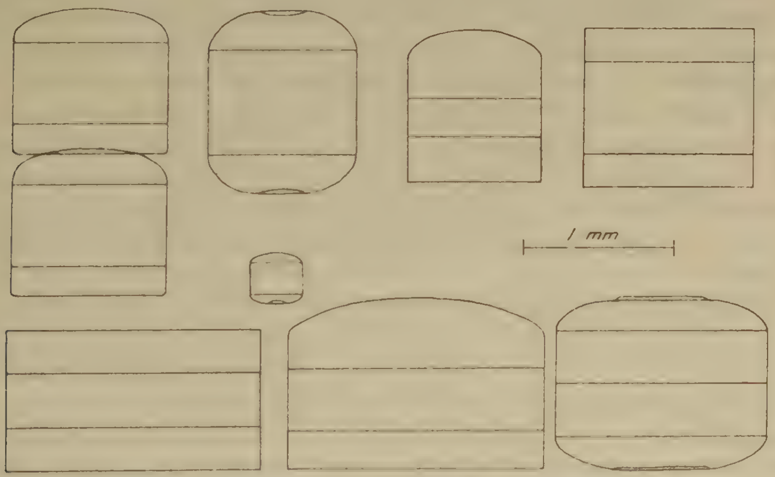

Fig. 3. Selected specimens of *Ethmodiscus rex* from *E. W. Scripps* Cruise 50, shown in girdle view to illustrate the wide variation in size and shape.

As indicated in Fig. 1, the average valve diameter in these samples tended to decrease from north to south. This decrease is illustrated in more striking fashion by the average diameters of all cells taken at stations 1 to 5 (140 mm), 6-12 (120 mm), and 13-30 (95 mm). Such size changes are characteristic of diatoms in the cycle from auxospore formation through successive cell divisions.

DISCUSSION

Although *Ethmodiscus rex* has not been reported previously as a constituent of the plankton in the temperate and tropical Pacific Ocean, it has been found in large numbers in bottom deposits. The importance of these deposits has been described vividly by MANN (1907), who stated that in a belt over 3,000 miles long from east to west, and perhaps 20 miles wide, between the islands of Guam and Luzon, the bottom deposits are composed chiefly, and often exclusively, of the remains of *Coscinodiscus rex*. The distance stated is in error, for it is roughly only about 1,500 miles from Guam to Luzon, but this is of minor importance.

Since phytoplankton organisms usually are present in tremendous numbers in relatively small volumes of water, it is customary to filter only small quantities, usually not more than a few litres, to obtain a satisfactory quantitative sample. Thus, species such as *Ethmodiscus rex*, with wide and relatively uniform oceanographic and seasonal ranges, but otherwise scarce, will be missed by conventional methods. A possible factor responsible for this relative scarcity may be the large size of the cells, limiting the diffusion of nutrient materials into the cell, thus limiting the rate of cell division.

It is not necessary, therefore, to postulate a short vegetative season to account for the rarity of *Ethmodiscus rex* in phytoplankton samples. The present data, indeed, seem to suggest that the vegetative season is continuous. There is no evidence that dense blooms of this species occur within the area surveyed, but this is not strange, for *E. rex* was found for the most part in the region of the California Current, beyond the effect of coastal areas of upwelling. The California Current is a wide body of water that moves sluggishly (SVERDRUP, JOHNSON, and FLEMING, 1942) and conditions conducive to the production of phytoplankton blooms would not usually be expected there. SVERDRUP and ALLEN (1939) showed that offshore water contains few diatoms, while inshore water may contain large numbers, off the southern California coast. They emphasized also that the " age " of the water was important. In the region of the equatorial currents, however, the circulation is such that the supply of nutrients in the photosynthetic zone is constantly being renewed. GRAHAM (1941) and KING and DEMOND (1953) have shown that in the open Pacific plankton is most abundant near the equator, where upwelling associated with the equatorial currents is a prominent phenomenon. This feature of the oceanic circulation may be associated with the occurrence of *Ethmodiscus* deposits in the western Pacific. The widespread distribution of this species in the area surveyed, if it is indicative of a similar distribution across the entire Pacific Ocean, would favour the occurrence of blooms, since presumably at least a few cells would be available whenever and wherever conditions favourable for rapid multiplication arose.

It is well to note, however, that RIEDEL (1954) indicates the possibility that the great bottom deposits of *Ethmodiscus* may be fossil. This certainly would seem to be the origin of the layer of *Ethmodiscus rex* found 793 cm below the bottom in a core from the Atlantic Ocean (WISEMAN and HENDEY, 1953).

The wide variation in cell size in the region covered by Cruise 50 of the *E. W. Scripps* raises a question concerning the homogeneity of the material. These samples were sorted and the measurements made by the author, and, although all the cells were not subjected to detailed taxonomic scrutiny, no obvious differences in sculpture were observed that might suggest the existence of more than one species. WIMPENNY

(1936, 1946) has indicated a range in cell diameter of from 20 to 120 microns for *Rhizosolenia styliformis* in the North Sea, but has concluded that two distinct varieties were represented. Lucas and Stubbings (1948) have stated that *Biddulphia sinensis* in the same region varies in size from 46 to 278 microns, and have noted that the size distribution of *Rhizosolenia* and *Biddulphia* over the region is related to the pattern of water circulation. Garstang (1937) also has commented on the value of *Rhizosolenia styliformis* as an indicator of water movements.

Although the available measurements of *Ethmodiscus rex* are too few to permit definite conclusions, they suggest several interesting possibilities. The regular decrease in average size from north to south is consistent with the pattern of oceanic circulation off the coasts of California and Lower California, for the California Current flows in a southeasterly direction, and successive cell divisions would lead, therefore, to a southward decrease in size. Further study may show that *Ethmodiscus rex* is a valuable indicator of the movement of surface waters in the Pacific Ocean.

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AUTHOR'S NOTE

While this paper was in press, it was suggested by Dr. WISEMAN after conversation with Dr. HENDEY, that perhaps the diatom in question was some species of *Ethmodiscus* other than *E. rex*. Drawings made in 1948 by the author and Dr. BRIAN P. BODEN were not sufficient to settle this point, and formalin-preserved specimens from Cruise 50 of the *E. W. Scripps* were so badly fragmented that reconstruction of the cells seemed practically impossible. Through the courtesy of Dr. BODEN, and DAVID KRAMER of the U.S. Fish and Wildlife Service, a single specimen was obtained, 1·5 mm in valve diameter, taken in a plankton net at station 130.40 (26° 09′N. Lat., 114° 08′W. Long.) on October 12, 1953. In the opinion of the author, after careful examination, this specimen unquestionably is identical with *E. rex* as described by WISEMAN and HENDEY (1953), on the basis of the following characteristics :

The valve margin has a narrow hyaline band. The valve surface bears radiating lines of puncta, 3 in 10 μ. Toward the valve margin and on the valve mantle these puncta are somewhat closer together, averaging about 4 in 10 μ. Toward the centre of the valve the lines of puncta give way to an irregular arrangement in which the characteristic tubular holes or pores described by WISEMAN and HENDEY appear. These pores are scattered more or less at random throughout the central area. The puncta on the girdle are slightly closer together than those on the valve, about 5 in 10 μ, and there are narrow hyaline bands on the margins of the girdle. At the ends of the girdle the lines of puncta appear to be flared out at the lower corners.

Dr. BODEN, in a recent letter, states that he is convinced that this material from the plankton is *E. rex*. He points out also that Dr. PAUL S. CONGER, of the U.S. National Museum, several years ago compared samples of our material with specimens in the Museum collection, and reached the same conclusion. Although the taxonomic status of the various diatoms assigned to the genus *Ethmodiscus* needs to be clarified, there is no evidence that the material described here differs from that examined by WISEMAN and HENDEY.

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Some effects of high hydrostatic pressure on apparatus observed on the Danish Galathea Deep-Sea Expedition

CLAUDE E. ZOBELL

Summary—Certain glass apparatus was adversely affected by hydrostatic pressure when submerged to great depths on the Danish *Galathea* Deep-Sea Expedition. Hollow glass balls, used to signal when collecting gear touched bottom, as well as reversing thermometers were broken by the pressure at depths exceeding 9,000 metres. Their failure, an implosion, was followed by a forceful explosion. An attempt is made to explain the explosion upon a basis of field observations. Capillary tubes used on the ZOBELL bacteriological water sampler withstood pressures exceeding 1,000 atmospheres, but unless filled with water they were plugged and broken by the intrusion of connecting rubber pressure tubing.

INTRODUCTION

THE Danish *Galathea* Deep-Sea Expedition of 1950-52 afforded opportunities to observe some effects of high hydrostatic pressure on certain apparatus submerged to depths exceeding 9,000 metres. Reversing thermometers, thick-walled glass balls, and bacteriological water samplers (ZOBELL, 1941) were found to be adversely affected by pressure of water in the Phillippine Trench, where at 10°13′N × 126°48′E the echo sounder on the *Galathea* recorded depths to 10,340 ± 100 metres (BRUUN, 1951).

In this same vicinity the *Snellius* Expedition had previously recorded a depth of 10,130 ± 100 metres at 9°42·4′N × 126°51·2′E (WÜST, 1951), the *Emden* recorded a depth of 10,400 ± 140 metres at 9°42·1′N × 126°52·1′E (MAUER, 1937) and the U.S.S. *Cape Johnson* recorded 10,497 ± 91 metres at 10°27′N × 126°39·5′E (HESS and BUELL, 1950).

GLASS BALLS

Submerged to depths exceeding 9,000 metres were several dozen hollow glass balls of the type used on the deep-water bottom signalling device described by ISAACS and MAXWELL (1952). The device (Fig. 1) consists of a mechanism for breaking a hollow glass ball upon contacting the sea floor. The resulting sound is detected by a hydrophone, thereby indicating that the gear, to which the ball-breaker is attached, has touched bottom.

The glass balls were carefully selected for uniform size and apparent freedom from flaws. They were approximately spherical in shape, having an average diameter of 70 mm and a wall thickness of 2 to 3 mm, except at the site of sealing off where the thickness ranged from 5 to 10 mm. Preparatory to employing the ball-breaker on the corer, dredge, sledge-trawl, grab or other deep-sea gear, the glass balls were submerged in the sea to test them for their pressure tolerance. Although none of the balls were adversely affected by pressures prevailing at 6,000 metres (approximately 600 atmospheres), several failed when submerged to depths exceeding 9,000 metres (Table 1).

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The hydrostatic pressure of sea water increases with depth by approximately 0·1 atmosphere per metre, the pressure-depth gradient being influenced to a maximum of about 5 per cent by latitude, temperature, and salinity. One atmosphere is equivalent to 14·696 psi, 760 mm Hg, 1·0332 kg/cm², or to 1·0133 bars.

It is noteworthy that 28 per cent of the 18 glass balls submerged to 9,200 to 9,300 metres were broken, whereas 62 per cent of the 26 submerged to 10,000 to 10,300 metres were broken. From 0·5 to 5 ml of water leaked into a few of the balls, as shown in the column headed " Took water " in Table 1. The absence of any obvious defects in the balls suggested that water might have been forced through the glass under the influence of pressure, but more careful inspection revealed that under the stress of pressure a capillary opening developed through the sealing-off point.

In all the balls submerged to 9,000 or more metres, there appeared small quantities of minute glass particles that chipped off the interior surfaces during compression or subsequent decompression. Extremely thin sections of glass up to several square centimetres in area peeled off the outside of some of the otherwise intact balls, like layers of onion skin. Such sections were found in the containers in which the balls were submerged. This peeling off may have occurred during submergence owing to unequal stresses set up in different layers of glass or it may have resulted from the force of water squeezed into the outer layers of glass.

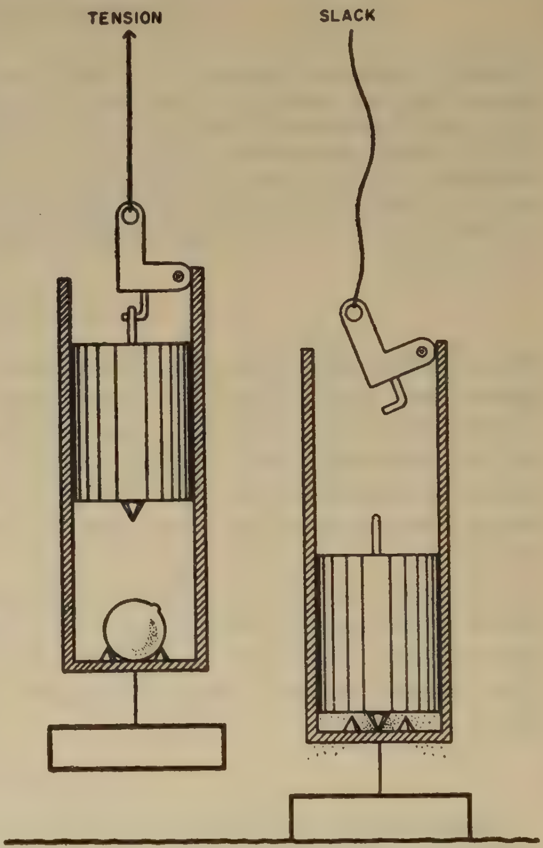

Fig. 1. Ball-breaker bottom-signalling device before (left) and after (right) hollow glass ball is broken by falling weight released by contact with the floor of the ocean.

Poulter and Wilson (1932) attributed the shattering of solid glass rods compressed to 15,000 atmospheres to the penetration of glass by water which fails to escape and subsequently expands when the pressure is released. Purportedly at such pressures water penetrates solid glass to a depth of several millimetres within 15 minutes. No breakage of glass occurred when glycerol or mineral oil was employed instead of water as the hydrostatic fluid, presumably because the larger molecules do not penetrate glass. Similarly Bridgman (1952) observed the " pinching off " of glass with the release of pressure, water invariably causing breakage at much lower pressures than such liquids as oils, alcohols, or glycerol. He concluded, however, that only extremely minute quantities of water penetrate glass at pressures up to 12,000 atmospheres. According to a private communication from Dr. J. W. WEST, extensive tests conducted by the Bell Telephone Laboratories for a period of several years failed to show any penetration of water through either Pyrex or type 7052 glass at pressures up to 600 atmospheres.

Table 1. Condition of glass balls submerged in sea to stated depth

Station number	*Station Location*		*Depth of submergence*	*Number submerged*	*Number broken*	*Took water*	*Number intact*
	Latitude	*Longitude*					
412	11°13′N	126°21′E	9,200 m	12	3	5	4
413	10°20′N	126°31′E	10,300 m	12	7	2	3
420	10°20′N	123°40′E	10,300 m	12	7	0	5
430	10°20′N	126°37′E	9,300 m	6	2	2	2
431	10°20′N	126°38′E	10,000 m	6	4	1	1
435	10°20′N	126°47′E	10,100 m	12	8	1	3

The fragmentation of the glass balls is similar in many respects to the collapse of Prince Rupert drops. These are made by heating a glass rod until it becomes syrupy. The resulting molten mass is dropped into cold water. Some of the molten glass drops fail to break, but are under high internal stress, the outside having solidified while the interior was still hot. As the interior cools and shrinks, high stresses are produced. The outer layers are under compressional stress that is approximately hydrostatic except at the very surface. When the surface of such a drop is broken, the whole mass collapses into very small fragments, most of the mass adhering together much like the remains of glass balls which collapsed under the influence of high hydrostatic pressure in the deep sea. In the case of Prince Rupert drops, the collapse is confined to the glass because the stresses are symmetrically disposed. In the hollow glass balls, bending stresses would cause a non-uniform collapse. After the initial break, at the point of highest tensile stress, there would be a general relief of the tremendous tensile stress present as a balance to the high compressive stress. This uncoiling of the tensile stress may result in the pulverizing of the glass and it may result in some explosive effect.

EXPLOSION RESULTING FROM BREAKING BALLS

There was evidence of an underwater explosion resulting from the breakage of hollow glass balls at high pressure. The balls were submerged in the sea by securing them in various kinds of receptacles lashed a few metres apart on the dredging cable. When encased separately in light-weight cloth sacks, ball breakage was indicated by the entire sack, except the fragment lashed to the cable, being torn off as if by a forceful explosion. This was confirmed by what happened when balls broke under water in sturdier receptacles.

Several balls were submerged separately encased in heavy-weight canvas sailcloth fashioned into sacks 25 cm wide and 30 cm long. Except for a pocket at the bottom designed to catch broken glass, the sack seams were loosely stitched in order to provide openings for the easy ingress and egress of water. Such sacks had jagged holes up to 6 cm long torn in their sides by balls that broke at water depths of 9,000 metres or more. Some of the stout sailcloth sacks had their bottoms torn off. Judging from the tensile strength of the sailcloth, a force of several hundred pounds would have been required to tear the sacks asunder. The tattered remnants clearly showed that the tearing force had been outward—an explosion. In a few of the tattered sacks small quantities of pulverized glass occurred in the bottom corners.

In an effort to recover more of the spoil resulting from broken balls and to learn more about the phenomena, a series of balls were submerged within tin cans, size 10 cm in diameter by 10·5 cm tall. The sides and lids of the cans were perforated with numerous holes, about 4 mm in diameter, in order to permit the free passage of water. Those cans in which glass balls collapsed at great depths were buckled and bent, whereas those carrying unbroken balls back to the surface were not perceptibly altered (Fig. 2). The former were irregularly accordion-pleated to give an hour-glass shape, and both ends were concaved. These changes must have resulted from the inrush of water when the balls collapsed. The walls and ends of such cans were deformed further by jagged holes, irregular in shape and space with their edges bent outward. This out-breaking of holes must have been caused by a forceful explosion, after the walls and ends of the cans had been bent inward. Remains of broken balls consisted of pulverised glass occurring in amorphous agglomerate, of various sizes.

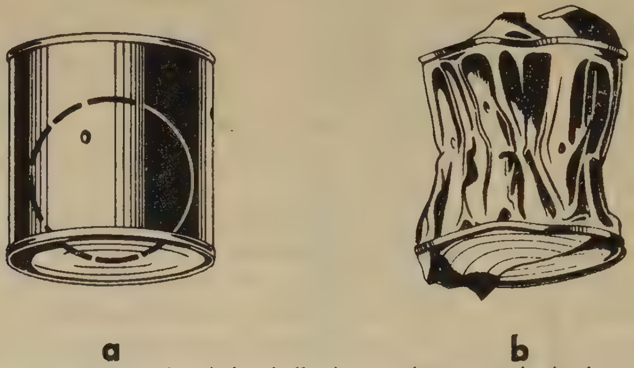

Fig. 2. (a) Perforated can with enclosed glass ball prior to submergence in the deep sea. (b) Appearance of can after breakage of glass ball by pressure at depth of 9,000 metres.

Virtually all of the spoil from several broken glass balls was recovered in thick-walled (3 mm) copper cans 8 cm in diameter by 8 cm high. Such cans were fabricated on the *Galathea* by BENT SORENSEN and A. THEGLER-JENSEN. The bottoms were brazed on and the tops were held in place by machine screws in such a position that there was an opening for the free passage of water. As in the more flimsy tin cans, balls breaking at great depths resulted in a collapse of the copper cans, accordion-pleated around the middle to give an hour-glass shape. Actually the inside diameter at the midsection of such cans was reduced from an initial 75 mm to 40 or 50 mm. The ends of the copper cans were also collapsed, the concavities having maximum depths ranging from 12 to 20 mm.

The interior walls were peppered with powdered glass, but no holes were torn through these stout copper cans by the explosion that followed the collapse of the glass balls. About three-fourths of the glass spoil remained in the copper cans as an almost impalpable powder or in loosely agglomerated lumps up to 15 mm thick. The latter could be picked to pieces or crushed with one's fingers. Microscopic examination of the spoil showed that it consisted of amorphous fragments ranging in size from less than one micron to many microns. The edges of most fragments were sharp, although some seemed to be slightly blunted, frittered, or fused.

Cloth adhesive tape, originally wrapped around the glass balls to secure them in the desired position in the cans, was found to be practically pulverized by balls, breaking. This provides further evidence for an explosion of the glass, because in a simple implosion the tape would have been peeled off and left behind more or less intact. Instead, it was so finely shredded that the fragments were difficult to identify, intermixed with pulverized glass.

EXPLANATION OF EXPLOSION

These observations tell something about what happens when hollow glass balls are broken by high hydrostatic pressure. Apparently the balls are compressed to a point of failure, this probably being primarily a function of diameter, wall thickness, kind of glass, and particularly lack of homogeneity which cause shear stresses in the structure. When the ball breaks, water rushes into the air space so forcefully that rigid containers like cans are collapsed. The explosion that follows in the wake of the implosion is not so simple to explain.

Part of this explosive force may be attributed to a reflected shock wave, the reverse of that which occurs when dynamite is discharged under water (COLE, 1948). Water rushing towards the centre of the recently broken glass ball may bounce back with appreciable force carrying with it some of the fragments of broken glass, but this force would probably be damped out before its influence extended much beyond the locus of the broken ball.

According to a private communication from Sir EDWARD BULLARD of the British National Physical Laboratory, the expression for the time T between successive oscillations of the bubble pulse following an underwater explosion is

$$T = 1{\cdot}14\rho^{1/2}\, W^{1/3}\, P^{-5/6}$$

where ρ is water density, W is initial energy of gaseous products of explosion, and P is the total hydrostatic pressure. P is ρgH where H is the water depth and W may be roughly equivalent to PV, which gives

$$\text{frequency} = 6{\cdot}54\,\frac{\sqrt{gH}}{r}$$

where r is the radius of the sphere.

According to OSBORNE (1947), shocks produced by a collapsing cavity in water are recurrent and multiple, the time interval separating them depending primarily upon the size of the cavity. Abruptness or violence of the shock is dependent upon the size of the residual air bubble around which the cavity collapses. A Pyrex glass bottle, with walls 3 to 5 mm thick, was broken with collapse of air bubbles only 1 mm or less in diameter.

BAKER (1940) described the breaking of glass jars partly filled with water by accelerating them so violently that a cavity was formed by the sudden departure of water. The bursting of the cavity caused the collapse of the glass jars.

Dr. CARL ECKART points out that the major energy from breaking balls must be liberated by the sudden collapse of the cavity, which contains some air. This collapse, however, is relatively slow because the cans are bent, not torn. Still considerable energy is liberated, and the inertia of the water that is set in motion will cause the pressure in the bubble, at the moment of smallest diameter, to be much higher than the ambient pressure. When a ball breaks at a depth of 10,000 metres, for example, the pressure to which the air bubble in the cavity is subjected will probably be considerably in excess of 1,000 atmospheres. The maximum ambient pressure is infinite when a spherical cavity is collapsed. This effect is similar to the " water hammer " action occurring when a water faucet is closed suddenly, resulting in the kinetic energy of moving water in the pipe being converted into pressure. This inrush of water at the moment of collapse could be expected to carry the fragments of broken glass into a very small volume and grind them together forcibly with the generation of considerable heat.

It has been calculated by Dr. T. R. FOLSOM that the maximum average temperature rise resulting from work done when a glass ball collapsed at 10,000 metres is about 480°C. The temperature in highly localized areas may be much higher. Cold water cooling the heated glass would result in thermal shock leading to fracturing.

Another explosive effect may result from the momentum or inertia of inrushing glass fragments carrying the latter through and beyond the locus of the ball (Fig. 3). The tendency would be for many of the glass fragments to collide as they approach the centre. Such fragments impinging upon each other and adhering in a state of semi-fusion may account for the amorphous lumps of loosely agglomerated glass fragments found as spoil. Since the glass balls are not homogeneous, there will be no smooth uniform progress of particles to the centre. Some particles will traverse the original outline of the sphere; others will bounce off the central or excentrically located mass. Owing to their random distribution, direction and difference in mass, not all of the flying fragments of glass would collide. Instead, many may continue to fly forward across the space formerly occupied by the ball and beyond with sufficient force to affect encasing containers.

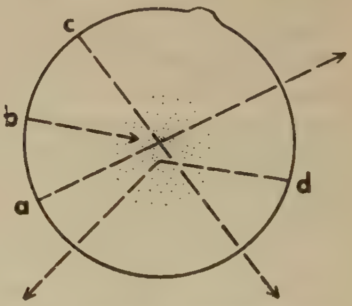

Fig. 3. Diagram illustrating theoretical trajectories of glass fragments when a hollow glass ball implodes (trajectories towards centre of ball) and explodes (trajectories outside of original outline of ball) under the influence of hydrostatic pressure.

This may be the movement of many glass fragments originating primarily from the inside of the balls, but additional explosive force may be generated by the glass fragments from the outside of the ball flying outward in all directions like countless springs uncoiling the instant the ball breaks, resulting in a sudden pressure change from nearly 1,000 atmospheres down to about one atmosphere. The compressibility of glass has been demonstrated by BRIDGMAN (1952), who found that this property increases with decreasing temperature. The temperature of the water in which the balls broke was approximately 2·5°C.

Another factor involved might be the manner in which the glass ball breaks. Assuming that the glass breaks at point of highest stress concentration before the glass envelope has been completely pulverized, the sea water would rush in primarily from one direction to fill the void. The inertia of the sea water in this direction with the glass particles, which by then would have been pulverized, would carry through toward the outer container with considerable kinetic energy. As a matter of fact, explosive force was randomly directional as indicated by highly irregular distribution and size of holes blown through the tin cans used as containers.

When two or more glass balls in close proximity were submerged to a depth of 9,000 or more metres, all or none of the balls in a common container were broken, although only about half of similar balls submerged a few metres apart to the same depths were broken. Presumably, the disturbance created when the weakest ball broke resulted in the collapse of adjacent balls.

OBSERVATION ON THERMOMETERS

Several protected reversing thermometers submerged to depths exceeding 8,000 metres were broken by the pressure. As with the glass balls that broke at such depths, there was evidence that an explosion followed the implosion. An inward bending of the metal housing surrounding the thermometer indicated a forceful implosion. An outward bending in local areas, or in some cases breakage of the metal housing, as well as the appearance of glass fragments in the surrounding metal parts, indicated an explosion. The spoil from the broken thermometers consisted of finely pulverized glass.

Not only was the protecting glass jacket (diameter 16 to 18 mm) broken but the two small-bore thermometers tubes within (one reversing and one auxiliary) were also broken. The failure of the latter must have resulted from the disturbance created by the breaking of the glass jacket or possibly the larger mercury-filled bulb, because such small-bore glass tubes can tolerate the greatest hydrostatic pressures occurring in the sea.

The spoil from one protected thermometer submerged to 9,000 metres was recovered almost intact. It appeared as a column of pulverized loosely fused glass. There were no discernible boundaries between the spoil from what had been the outer jacket and the inner thermometer tubes.

It was impractical for economic as well as for logistic reasons to submerge enough thermometers to get information of statistical significance on the exact depths of failure of various instruments. It may be noteworthy, however, that all of the six American-made (*Kahl Scientific Instrument Corp.*) thermometers submerged to 9,000 or more metres failed. Likewise two of the German-made (*Richter and Wiese*) thermometers were broken by pressures at depths exceeding 9,000 metres. The one and only Japanese-made (*Watanabe Keiki Mfg. Co.*) thermometer submerged to 9,000 metres was broken by pressure. A few temperature readings were made with English-made (*Negretti Zambra*) thermometers at depths exceeding 10,000 metres. The latter are smaller in diameter than other kinds of reversing thermometers. Their smaller diameter may account for their pressure tolerance, although it may have been purely happenstance that the few selected for the deep-sea stations were better annealed. Those that failed might have had slight variations in thickness at the sealing-off point, resulting in high tensile and shear stresses in the glass, predisposing to failure when the thermometers were subjected to high pressures.

BACTERIOLOGICAL WATER SAMPLERS

Water samples for bacteriological analyses were collected from depths exceeding 10,000 metres by means of apparatus described by ZoBell (1941). Essentially the bacteriological water sampler consists of a pear-shaped collapsible rubber bulb, having a capacity of about 300 ml, fitted with a hermetically sealed capillary glass tube by means of a short length (15 cm) of flexible rubber tubing. When lowered to the desired depth, attached to the hydrographic wire by means of a brass holder, a messenger was dropped to activate a mechanism which broke the glass tube thereby permitting the rubber bulb to fill with water.

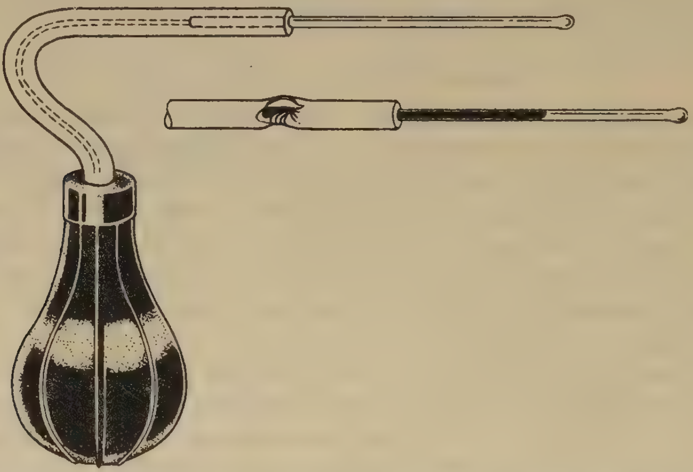

Fig. 4. Collapsible rubber bulb, pressure tubing, and hermetically sealed glass tube assembled for collecting water sample aseptically from any desired depth for bacteriological analysis. Inset shows failure at great oceanic depth due to water pressure's pushing rubber tubing into the open end of glass tube until wall of rubber tubing was punctured.

Although the capillary glass tube, having a bore of 2 mm and an outside diameter of 4 mm, withstood the highest pressures encountered on the *Galathea* Expedition, there were four failures caused by the rubber tubing's (1 mm bore and 4 mm wall thickness) being forced by water pressure into the open end of the glass tube (Fig. 4). Upon being collapsed over the open end of the glass tube, pressure pushed the thick-walled rubber tubing into glass tube until the rubber tubing was ruptured, thereby permitting the bulb to fill with water at the depth where the failure occurred. No such failures occurred at water depths of less than 8,000 metres. This defect was corrected by having the capillary tube filled with a few drops of sterile water prior to submerging the bacteriological sampler.

Some of the 300-ml rubber bulbs submerged to depths exceeding 9,000 metres reversibly lost some of their elasticity or resiliency ; they returned only slowly to their normal pear-shape after being collapsed. Consequently, one could not know at what depth such bulbs so affected by pressure filled with water. Ordinarily the rubber bulbs are filled to capacity with water within a few seconds after being opened under water by breaking the capillary tube. As a rule they are hauled to the surface with water being ejected owing to the decrease in external pressure.

Further investigations are required to determine the extent to which various kinds of rubber or other elastomers are affected by deep-sea pressures. There seems to be a difference in the pressure tolerance of different rubber receptacles. According to THIESSEN and KIRSCH (1938), caoutchouc commences to crystallize at pressures ranging from 10 to 25 atmospheres at 7° to 10°C.

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The assistance of the scientific staff and crew of the *Galathea* who helped make these observations is acknowledged. Also acknowledged are the constructive criticisms of Sir EDWARD BULLARD, National Physical Laboratory, and of several of my colleagues at the Scripps Institution of Oceanography, particularly Drs. CARL ECKART, ALFRED B. FOCKE and T. R. FOLSOM. Several helpful suggestions were also received from Drs. J. W. WEST and J. R. WILSON of the Bell Telephone Laboratories.

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Organic Detritus in the Metabolism of the Sea

DENIS L. FOX

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Organic Detritus in the Metabolism of the Sea

DENIS L. FOX

Having moved to this country from his native England in 1905, Dr. Fox received his training at the University of California and Stanford University. From 1925 to 1929 he was a chemist with the Standard Oil Company of California; since 1931 he has been at the Scripps Institution of Oceanography, where he is now professor of marine biochemistry. In 1938–39 Dr. Fox was a Rockefeller Research fellow, and in 1945–46 a Guggenheim fellow. He is an occasional consulting biochemist and the author of Animal Biochromes and Structural Colors.

THE earth's hydrosphere, comprised largely of the oceans, is a heterogeneous system of particulate substances, ranging in dimensions from visible aggregates down to colloidal micelles of solid, liquid, and gaseous character, dispersed in an aqueous saline solution. The salt concentration, moreover, shows wide variation, for example, from a few fractional parts per million in mountain lakes and streams, through increased amounts in estuaries and river mouths, reaching values of 3.3 to 3.5 percent in the sea, and values nearly 10 times as high, or full saturation, in land locked salt waters.

The distribution and concentration of leptopelic (*1*) or finely suspended organic and inorganic materials in natural waters likewise show wide variation; minimal quantities are present in clear alpine lakes, while the highest concentrations prevail in stagnant tropical or subtropical swamp waters. Intermediate but greatly varying amounts are encountered in the oceans. The relative populations of microplanktonic organisms and the corresponding concentrations of their particulate detritus are partly responsible for the various green, yellow-green, ruddy or brownish colors of near-shore areas, while the blue-green or blue shades of deep oceanic areas represent the clearest waters.

The relative quantities of organic (for example, protein, lipid, polysaccharide, and humus) and inorganic leptopel (insoluble silicates, phosphates, carbonates, hydrated oxides, and so forth) and the ratios between the two kinds of suspended materials exhibit high variability even in temperate regions; the kinds, concentrations, and relative proportions between these two major classes depend upon temperature, relative density, water movement, season, light, and distance from shore (*2*).

Concentrations of organic leptopel in marine waters may vary from a few fractional parts per million in midocean or at great depths, through values of several milligrams per liter near the surface of near-shore areas, and up to tenfold or more in surface slicks or just beneath them. Quantities of particulate organic matter, adsorbed as pelogloea to solid surfaces, may exceed the amounts suspended in water by 10 times in beach sand, which commonly involves about 1 percent organic matter or by 100,000 times in fine silt or bottom muds (*1*).

The ocean might be regarded as a vast, loosely integrated but complex and actively metabolizing "cell," its somewhat salty but organically dilute "sap" gaining some of its dissolved nitrogenous and phosphatic nutrients from land drainage, some directly from electric storms and washing of the air by rain, and a considerable fraction through bacterial agents in the marine biochemical cycle. The ocean's fluid medium executes many well-defined currents, thus implementing a vast, complex circulatory system (*3*). Thus nutrients, dissolved gases and solid or semisolid inclusions are transported, while fluid masses of differing original salinities and temperatures receive partial mixing. A "respiratory" exchange of CO_2 and O_2 takes place between the ocean's surface and the atmosphere, and an immense "transpirational" cycle of water likewise occurs through evaporation and reprecipitation as rain. Photosynthesis is carried out on an enormous scale by green phytoplankton and by sea weeds of the euphotic zone. The circulating watery fluid bathes innumerable organized tissues, maintaining their osmotic integrity, bearing the finely divided food particles for their direct or ultimate somatic maintenance, while providing for the dispersal of their reproductive products and their cata-

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bolic wastes. Certain solid, more chemically inert wastes may be gradually "excreted" from the central mass, finding their way to the ocean floor.

High variability within the oceanic cell applies not only to the organic content of its waters but to local differences in the intensity of metabolism. Minimal levels of total organic carbon and organic nitrogen may prevail, for example, both at warm equatorial latitudes and in deep, cold waters of the central Pacific, while the total biochemical turnover may reach its peak in temperate latitudes at and near the land mass. There are great seasonal variations in the metabolism of the sea in polar regions, biochemical processes reaching their low ebb in the winter freeze, and achieving a maximum with the spring thaw.

This article (*4*) is primarily concerned with the distribution, measurement, and metabolism of organic matter in its suspended (leptopelic) state and in its adsorbed (pelogloeal) condition. Organic matter in true solution is commonly but a minor fraction of the total (*5*). In practice, the colloidal or other particulate material is collected on microfiltrational membranes of cellulose acetate and nitrate, whose porosity retains bodies as small as 0.5 μ, or preferably 0.2 μ, in diameter. Staining, washing, and drying the filtered residue *in situ* are followed by homogenizing the membrane to light by the addition of an inert fluid of equal refractive index. Numbers, size-distribution, and total volume and weight of cellular material may then be estimated microscopically. Ashing of sufficient material so collected will yield values of inorganic leptopel concentration (*2*).

Organic leptopel is determined chemically by passing the water through a layer of fine, inert inorganic powder, for example, MgO and refined celite, capable of adsorbing the finest colloidal micelles, even such as molecular hemoglobin with a mean diameter of only 5 mμ (*5*). Complete oxidation of the collected sample will yield measurable CO_2 and NH_3, or will leave a titratable quantity of standard oxidant, such as chromic acid. Alternatively, total ether-soluble lipids or total diagnostic pigments such as carotenoids or porphyrins may be recovered and measured.

The common progenitor of the first living, reproducing biochemical complexes involved the hydrosphere, a vast heterogeneous "cell" bearing a great diversity of organic and inorganic compounds from which the newly formed aggregates were able selectively to assimilate their nutritional supplies (*6*). Unorganized organic matter greatly preponderated over the living kind and still does, but, as organisms have evolved, great changes have occurred in the kinds of nonliving organic compounds of the environment. It is profoundly questionable whether living matter is still arising *de novo* in today's world, for there is now a plentiful supply of atmospheric and dissolved oxygen, as well as a ubiquitous population of microflora, both of which agencies would promote the early destruction of any new, labile molecules (*6, 7*). The lifeless organic matter of the environment is made up largely, if not totally, of biochemical detritus, that is, from catabolic wastes, undigested residues and parts of dead organisms.

Large and diversified populations of organisms will be supported in regions of high content of unorganized matter. The two so-called "states" of organic matter exist inseparably in a dynamic state of flux, barring ephemeral dislocations from outside influences. Still, in any relatively equilibrated system of this kind, or in the marine world taken as a whole, the mass of unorganized detrital organic material must exceed considerably that of the collective living entities. Such a condition is a cumulative heritage from the primary photosynthesizers and is indispensable for the continuance of life as we know it.

Since true organic solutes can hardly exceed a small fractional part per million in most marine waters (*5*), they are inaccessible directly to animals and are doubtless consumable only very slowly by bacteria (*8, 9*). But organic matter in a dispersed, suspended condition, whether free or adsorbed to inorganic suspensoids, is a readily utilized source of food, since filtering or suspension-feeding animals are able to resolve and consume the disperse phase of a fine "puree," while they cannot utilize a thin tea or "consommé" of true solutes.

Let us survey briefly the metabolic activities of three representative marine animal species that feed upon suspended or adsorbed detrital matter. The sea mussel, *Mytilus californianus,* is a typical suspension-feeding bivalve; the polychaete beach worm, *Thoracophelia mucronata,* is a wholesale swallower of sand, and the intertidal snail, *Littorina planaxis,* exemplifies a large class of "scrapers" that cut away siltstone and its surface layer of pelogloea by means of a horny tongue or radula.

A population of 1 million mussels, for example, on an area of rocky surface, aggregating about ¾ acre, will, during their second year of life, filter the finely suspended material from at least 22 million tons of their environmental water, equivalent to a volume of ocean water about 1 mi square and 25 ft deep. If the suspended organic matter in this water amounts to about 5 ppm, the mollusks remove some 121 tons of such material. Augmenting their own collective weight of organic matter by 4.1 tons, they yield a ratio of filtered to incorporated organic matter of about 3.3 percent. By no means all of the filtered organic matter, however, is ingested by the mussel; much of it may be rejected by the gills and palps. Furthermore, a sizable portion of the organic material swallowed is not digested, for example, humus, chitin, cellulose, and other refractory materials, as well as numerous living dinoflagellates bearing impervious envelopes (*10–13*).

Manifestly these factors will combine toward a greater efficiency on the part of the consumer. An alternative but still conservative value for this efficiency may be derived from the data estimated by Fox and Coe (*14*) for a community of mussels, half of which are in their first year of life, about a third in their second year, and the remaining sixth in their third. A hundred mussels of such an age distribution will void an estimated total of 1960 g of feces in a year and will manufacture 210 g of gametes, while depositing a total of 139 g of new somatic tissue, all figures being on a calculated ash-free, dry-weight basis. These values yield a quotient of 17.6 percent efficiency. However, since the fecal weight, taken as the denominator, will be exceeded by the weight of material actually ingested, the figure for efficiency must be taken as only roughly approximate.

Benthic suspension-feeders, such as bivalves, tunicates, sponges, and the like, remove vast amounts of fine organic detrital matter from the sea, assimilating significant fractions of it as new tissue, while eliminating the greater portion in impacted fecal aggregates. Some of these aggregates settle to the floor of the sea, there enriching the nutritional supplies of mud-dwelling animals and the resident microflora. Freely swimming suspension-feeders, including many smaller crustaceans and salps, doubtless occupy an outstanding role in that portion of the marine biochemical cycle which involves organic leptopel.

The burrowing annelid worm, *Thoracophelia mucronata,* occupies damp sand in large numbers along the western North American coast, where it continuously passes sand through its alimentary tract, utilizing as food the relatively small quantities of colloidal and other finely divided pelogloeal material adsorbed from the water to the siliceous surfaces. A characteristic worm bed, 10 ft wide, may extend indefinitely along a sandy shore, limited chiefly by rocky barriers.

A worm bed 1 ft deep, aggregating 500 mi in length and 10 ft in width (that is, occupying an area of 1 mi^2), contains 2.64×10^7 ft^3 of damp sand, weighing 1.41×10^6 tons when dry. An average population of 3000 worms 1 ft^2 will give an aggregate of nearly 8×10^{10} animals in the bed, weighing a total 3500 tons. Since each individual may ingest about 2100-fold its own net weight annually, the community will be capable of cycling 7.3×10^6 tons of sand per year. Of the 7×10^4 tons of available organic matter associated with this quantity of sand, 700 tons will be converted into new tissue, assuming an annual life-cycle. This species thus demonstrates a value of about 1 percent for the ratio of ingested to newly added organic matter. A 2-year life-cycle would halve this value for the apparent efficiency. While not perhaps to be regarded as completely typical, this polychaete species may represent, in a general way, the metabolic pattern of sand- or mud-eating invertebrates (*15*).

We may consider, as a final example, a typical scraper or radulate feeder, the intertidal snail *Littorina planaxis* (*16*). This common periwinkle feeds on the small quantities of algae and pelogloea adhering to impacted Eocene and Cretaceous siltstone. It is a major agency in the erosion of the siltstone and in its return to the sea in finely comminuted form. Populations of the snail on tidally exposed siltstone near La Jolla, California, have been estimated to number about 333 animals per square meter. A snail with an 8-mm shell length (the predominant size) augments its tissue dry weight by about 7.2 mg annually. It ingests approximately 2336 mg of the siltstone per year. Since the consumed substrate involves about 2.6 percent organic matter, the ratio of newly incorporated to ingested organic matter is $(7.2 \times 100)/(2336 \times 0.026) = 11.9$ percent.

While metabolizing the organic material at this fairly efficient level, the calculated 8.6×10^8 snails on a square mile of wet siltstone will erode, in the period of a year, approximately 2200 tons, or 3×10^4 ft^3, of the siliceous material, fixing as tissue material, 6.82 tons of the total 57.2 tons of organic matter available.

The casual observer knows that the operation of this biological agency does not effect a homogeneous removal of a fractional millimeter per year from the surface of this stone, but instead results in the production of many roundish excavations of widely varying circumference and depth. These erosion basins occur not only in horizontal areas, where they remain filled with intertidal water, but appear in smaller sizes in sloping or even vertical surfaces. It has been estimated that a theoretical standing community of 100 *Littorina* *lanaxis* of average (8 mm) shell length, would e capable of excavating a liter of siltstone in 11.5 r (*16*).

These random examples will perhaps provide ome idea of the magnitude of only three diversiied physical and chemical operations, continuing n a vast scale through the activities of countless narine invertebrate species whose nutrition deends upon ample supplies of suspended or adorbed detrital organic matter.

Finally, in order to gain some concept of the nass of organic leptopel involved in the waters of he world oceans, let us adopt a relatively conservtive value of 1 ppm as its average concentration *1*). If the density of this organic detritus is aproximately equal to that of water, and if we apply he value of 1370×10^6 km^3 (about 330×10^6 mi^3) s the aggregate volume of the world's oceans (*3*), ve have a product of $(5280)^3 \times 330 \times 62.4 = 31$ 10^{14} lb, or 1.5×10^{12} tons. This figure, even omiting the mass of pelogloeal organic matter adorbed to immersed surfaces, is suggestive of the uantity of suspended organic detritus which, servng as a primary or secondary source of food, is nvolved in the vast and perpetual metabolic cycles f carbonaceous matter in the sea.

Some approximate values derived from estimaions by Riley and others (*17*) would suggest that he foregoing provisional value may not be far out f line. If, for example, a relatively high value, 00 g, of organic carbon (or roughly 400 g of rganic matter) may be taken to represent the uantity produced annually by marine phytoplankon beneath each square meter of ocean surface, hen applying the factor of 360×10^{12} m^2 for the otal ocean surface yields a value of 14.4×10^{16} g, vhich is equivalent to about 3×10^{14} lbs, or $1.5 \times$ 0^{11} tons, of organic matter synthesized per year.

The estimated minimal standing crop of susended organic matter exceeds this quantity by tenfold. Adding the estimated total productivity of land plants would augment the phytoplankton value by only about 3×10^{10} tons per year (*18*), or roughly 17 percent, giving an aggregate of about 1.8×10^{11} tons of organic matter synthesized per year on land and sea.

Since the foregoing value for total annual marine phytoplankton productivity may be somewhat high, and the estimated value for the standing crop of organic matter relatively low (that is, referring only to suspended, not to sedimentary or adsorbed, organic matter) the persistent quantities may exceed the annual synthesis by more than one order and perhaps by as much as two orders of magnitude.

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DISTRIBUTION OF THE FORAMINIFERA IN THE NORTHEASTERN GULF OF MEXICO

By

Frances L. Parker

(With Thirteen Plates)

CAMBRIDGE, MASS., U.S.A.
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August, 1954

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No. 10 — *Distribution of the Foraminifera in the Northeastern Gulf of Mexico*

By

Frances L. Parker

CONTENTS

Page

Introduction 454
Location of Stations 455
Method of Sampling and Laboratory Work 455
Temperature Distribution 458
Salinity Distribution 459
Depth Facies Based on Benthonic Species 459
  Introduction 459
  Facies 1 461
  Facies 2 464
  Facies 3 466
  Facies 4 467
  Facies 5 469
  Facies 6 471
Lateral Changes in Faunas 472
Distribution of Living Benthonic Species 473
Distribution of Planktonic Species (Living and Dead) . . . 476
Benthonic Species 479
  Introduction 479
  Discussion of Species 481
Conclusions 546
Bibliography 547

ILLUSTRATIONS

Fig. 1. Northeastern Gulf of Mexico showing station locations . . 456
Fig. 2. *Sigmoilina* sp. 500
Figs 3-9. Generalized distributions of benthonic Foraminifera by depth . . . . (at back)
Table 1. Temperature and salinity in facies 1-6 461
Table 2. Living benthonic population in per cent of total benthonic population in traverses I-IV 475
Table 3. Locations of stations giving depth and type of sampling gear used . . . . (at back)

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Tables 4, 5. Percentage distribution of benthonic Foraminifera in traverses I and II . . . . (at back)
Tables 6-8. Percentage distribution of benthonic Foraminifera in traverses III and IV . . . . (at back)
Tables 9-11. Percentage distribution of benthonic Foraminifera in traverse V . . . . (at back)
Tables 12-14. Percentage distribution of benthonic Foraminifera in traverse VI . . . . (at back)
Tables 15-17. Percentage distribution of benthonic Foraminifera in traverse VII . . . . (at back)
Tables 18-20. Percentage distribution of benthonic Foraminifera in traverse VIII . . . . (at back)
Tables 21-23. Percentage distribution of benthonic Foraminifera in traverses IX-XI . . . . (at back)
Table 24. Percentage distribution of planktonic Foraminifera in traverse VII . . . . (at back)
Table 25. Distribution of living benthonic Foraminifera in traverses I and II . . . . (at back)
Table 26. Distribution of living benthonic Foraminifera in traverses III-V . . . . (at back)
Table 27. Distribution of living benthonic Foraminifera in traverses VI and VII . . . . (at back)
Table 28. Distribution of living benthonic Foraminifera in traverses VIII-XI . . . . (at back)
Table 29. Distribution of living planktonic Foraminifera in traverses II-VI . . . . (at back)
Table 30. Distribution of living planktonic Foraminifera in traverses VII-XI . . . . (at back)
Plates I-XIII . . . . (at back)

INTRODUCTION

The distribution of the Foraminifera in the northeastern Gulf of Mexico has been studied to supplement the previous report by Phleger and Parker (1951) on the northwestern Gulf of Mexico. The area studied extends from the Mississippi River to Cedar Keys, Florida and southward from Cedar Keys excluding the continental shelf but extending westward from a depth of 100 m. in a series of zigzag traverses south to the Dry Tortugas. It includes roughly the region between N. Lat. 25-30° and W. Long. 83-90°.

In studying the foraminiferal distributions emphasis is given to establishing criteria by which the various environments may be recognized. In order to do this the death assemblages of planktonic and benthonic Foraminifera have been studied throughout the area and the living assemblages for a large part of it, excluding the continental shelf stations east of Mobile Bay, Alabama. Temperature and salinity data are given. The sediments are being studied by H. C. Stetson and no description of them is given at this time.

The samples were collected by H. C. Stetson using the Woods Hole Oceanographic Institution R/V ATLANTIS. Study of the Foraminifera has been supported by the Office of Naval Research (Project NR 081-050, Contract Nonr-233 Task I). H. C. Stetson, F. B Phleger and W. R. Walton have read the manuscript and made valuable suggestions. Miss Ruth Todd and A. R. Loeblich of the U. S. National Museum have kindly compared specimens of several species with types deposited at the museum. Miss J. F. Peirson assisted with the laboratory work and drafting, and N. M. Curtis photographed the specimens for illustration.

LOCATION OF STATIONS

Figure 1 shows the locations of the stations, and Table 3 gives geographic position, depth in meters, and sampling gear used for each station. For convenience the samples have been divided into eleven traverses. *Traverse I* includes stations 201-211, from 51 m. to 430 m.; *traverse II*, stations 3-24, from 33 m. to 3017 m.; *traverse III*, stations 25-37, from 22 m. to 2388 m.; *traverse IV*, stations 212-225, from 20 m. (Mobile Bay) to 62 m.; *traverse V*, stations 74-97, 99-105, from 20 m. to 1417 m.; *traverse VI*, stations 38-73, 106, from 20 m. to 2697 m.; *traverse VII*, stations 174-191, 107, from 22 m. to 3017 m.; *traverse VIII*, stations 146, 148-172, from 12 m. to 3164 m.; *traverse IX*, stations 137-145, 108, from 183 m. to 3160 m.; *traverse X*, stations 126-136, from 950 m. to 3180 m.; *traverse XI*, stations 1, 2, 110-124, from 139 m. to 3283 m.

METHOD OF SAMPLING AND LABORATORY WORK

The samples were collected in 1951 during the months of February and March. Four types of sampling gear were used.

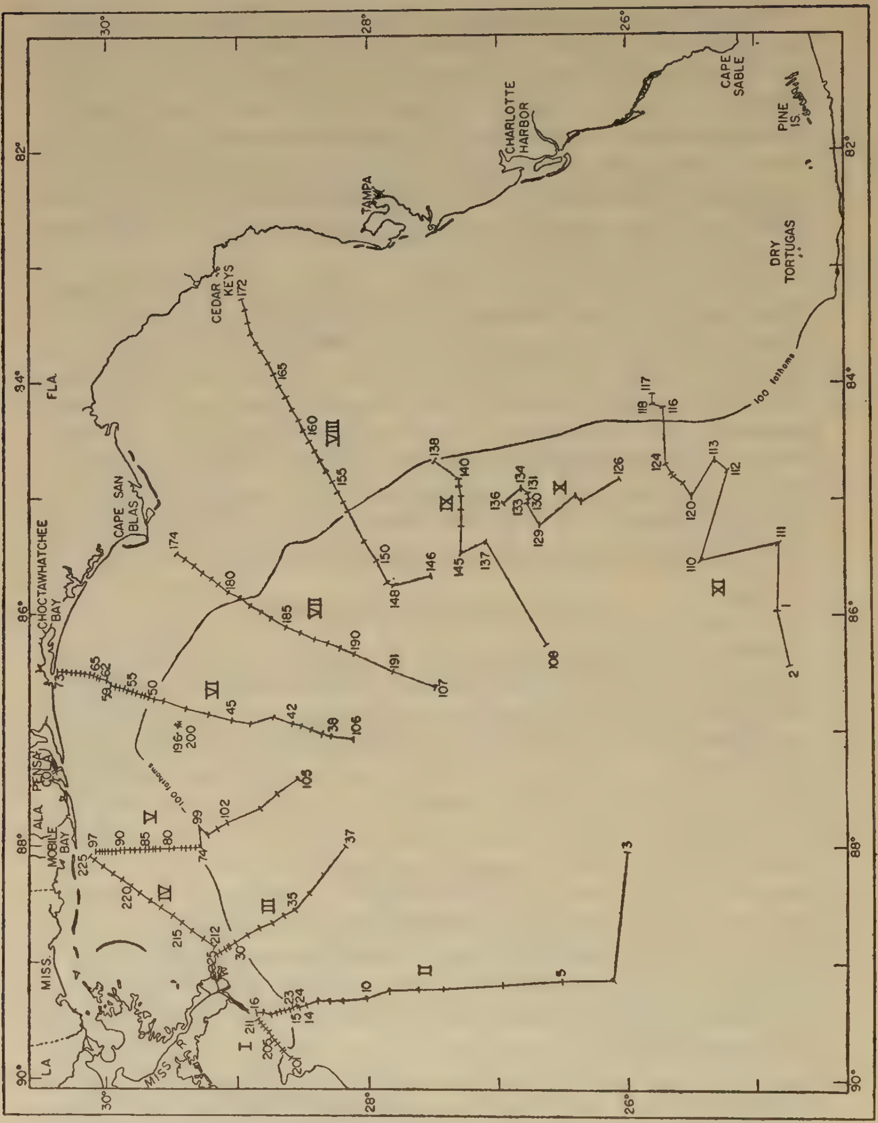
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Fig. 1. Northeastern Gulf of Mexico showing station locations.

The Phleger sampler (Phleger, 1952, p. 321) was used where possible. On the continental shelf where the material is shelly and heterogeneous, samples were taken with the orange peel dredge (Phleger, 1952, p. 320) and the Stetson-Iselin sampler (Stetson, 1938, p. 7). In a few places the underway sampler designed by Ewing *et al* (1946, p. 925) was used.

When samples for the study of Foraminifera have been taken with such diverse types of gear, uniformity of results cannot be guaranteed. Such samples do not cover a uniform area and thickness of sediment. An attempt has been made, however, to use equal volume samples. In short cores taken with the Phleger sampler a section from the top of the core including half the surface area to a depth of approximately 2 cm. was taken, giving a sample of approximately 10 cc. volume. Total populations of Foraminifera in the samples taken with other tyes of gear were calculated for 10 cc. of dry material. This material was composed of sand and shells with little or no fine material and had approximately the same volume wet or dry. Samples containing shelly material cannot be measured accurately and for this reason the total populations given on Tables 4-24 should be regarded as representing approximations rather than exact numbers.

Neutralized formalin was added to the short cores at the time of collection so that the Foraminifera living at that time could be studied. After taking the samples from the cores additional formalin was added. It has been found necessary also to add a small amount of sodium carbonate to prevent the formalin from becoming acidic, especially if considerable time is to elapse before the samples are analyzed. Frequent checks of the pH of such samples should be made to insure that the basic character is maintained, a pH of 7-8 being the most satisfactory. Only a few samples exclusive of those taken with the Phleger sampler were preserved in formalin and counts of the living populations could not be made.

The samples were prepared by washing through a brass sieve having average openings of 0.074 mm. More accurate population counts of planktonic Foraminifera can be made using the residue left on a screen having larger openings of 0.114 mm., but this was not done in this case in order that the population counts would be comparable with those made in the study of the northwestern Gulf of Mexico area (Phleger, 1951). In counting the tests of planktonic forms from this fine material, however, small unidentifiable forms are of necessity omitted. Population counts of living Foraminifera were made using the rose bengal staining technique described by Walton (1952).

TEMPERATURE DISTRIBUTION

There is little available information on temperatures in the northeastern Gulf of Mexico. The temperatures found in the shoalest 130 m. of water depth have been taken from a compilation of data made by Adams and Sorgnit (1951). The data used were from all available bathythermograms for the winter months, January, February, and March, and the summer months, July, August, and September. The coverage of the area is not complete and there are almost no data for the region east of 87° W Long. and north of 29° N Lat. It is probable that bottom temperatures deeper than 130 m. are similar to those in the northwest Gulf of Mexico and these have been taken from Phleger's (1951) analysis of data obtained by the cruises of the MABEL TAYLOR in 1932 and the ATLANTIS in 1935 and 1947. Additional information may modify the situation as described below but it is believed to be a good approximation of the actual conditions.

In winter, isothermal water extends to depths of 15-100 m., in summer to depths of 12-15 m. The seasonal effect may disappear as shoal as 50 m. or may extend to a depth of 150 m. or more. Since present data are limited to the upper 130 m. of water, the exact depth of seasonal effect cannot be ascertained since it is still observable below this depth in many areas. In the northwestern Gulf of Mexico the maximum depth of the seasonal effect is 200 m. according to Phleger (1951, p. 15) and it is probable that it is similar in the northeastern area.

The following minimum and maximum bottom temperatures for the continental shelf shoaler than 50 m. have been deduced from data given by Adams and Sorgnit for the upper 50 m. of water in the various areas within the 100 fathom curve. These would represent average temperatures and would probably be exceeded in many seasons, especially close to shore. Minimum bottom temperatures from 0-50 m. are: 18°C. southeast of the

Mississippi Delta; 21°C. south of Mobile Bay; 18°C. just west of Cape San Blas; 21°C. near Cedar Keys and along the coast of Florida to the south. Maximum bottom temperatures from 0-50 m. are 31-32°C. southeast of the Mississippi Delta, 28°C. south of Mobile Bay, 28-31°C. along the west coast of Florida.

As nearly as can be ascertained from the available data, the temperature at the lower limit of seasonal effect varies from 18°C. to 21°C. Below this point it diminishes to the bottom of the permanent thermocline at 800-1000 m. to 5°C., and deeper than this shows no significant change.

Surface temperatures in the Gulf of Mexico according to Fuglister (1947) range from an average minimum of 20°C. in February to an average maximum of 29°C. in August.

SALINITY DISTRIBUTION

There are few salinity data for the area; the following information is taken from Parr (1935). Nearshore salinities in the upper 50 m. of water are <24 o/oo southwest of the Mississippi Delta (at the position of traverse I), <35 o/oo south of Mobile Bay, and >36.25 o/oo on the continental shelf along the west coast of Florida. These figures might be lowered in the Mississippi Delta area and perhaps to a lesser extent south of Mobile Bay during times of exceptional runoff and mixing but normally there is a steep positive salinity gradient where fresh river water spreads over the surface. Parr gives no data for the shallow area between Cape San Blas and Cedar Keys but it is probable that the salinities are approximately 36 o/oo as they are farther south. At 200 m. the salinity is approximately 36 o/oo, and below this point it diminishes to about 35 o/oo at 400 m. with no significant change deeper.

DEPTH FACIES BASED ON BENTHONIC SPECIES

Introduction

Six depth facies based on benthonic species can be detected in the area. These have been given equal importance in discussion but some are more important than others. An example of this is the separation of facies 2 and 3; they perhaps should be combined to indicate a major facies change between 80 m. and 150 m. Benthonic facies boundaries are found at: 80-100 m., 130-150 m., 180-220 m., 350-600 m., 900-1000 m. There is a less distinct boundary at 30-50 m. which is considered here to represent a sub-facies boundary in facies 1, and a second one at 250 m. in facies 4. All boundaries are gradational and not sharply defined. Deeper than 1000 m. there are various gradual changes to the greatest depth sampled at 3283 m.; these are not concentrated at any particular depth and will be discussed under facies 6. There is little doubt that a close sampling grid in the shoal area between the shore and 100 m. would reveal more changes in the continental shelf faunas, but such fine gradations cannot be detected in the present reconnaissance sampling pattern. The facies changes indicated here should, therefore, be considered as gross changes. Foraminifera displaced from shoal areas are sometimes found in deep samples. This is especially true at the base of the escarpment parallel to the coast of Florida which is cut by traverses IX-XI. These displacements can be easily detected in analyzing Tables 4-23 which give the percentage distribution of the benthonic species. These tables list the benthonic species as percentages of total benthonic population and give the totals of planktonic Foraminifera found at each station.

In the following section each facies is discussed separately giving faunal characteristics and a detailed discussion of its appearance or non-appearance in each traverse. In this way lateral changes can be indicated for the various depth facies. These lateral changes also will be summarized in a later section. Figures 3-9 show generalized depth ranges of most of the species included in the population counts and the traverses in which they are found. All discussion of occurrence or non-occurrence of any species is based on its presence with a frequency of 0.1 per cent or more of the total population and it is, therefore, possible that the species may occur rarely under other conditions than those listed. Many species which appear only spasmodically in population counts are omitted as such and listed under "miscellaneous spp." in the tables. Table 1 gives a summary of temperature and salinity conditions in the various facies. These should be regarded as approximations.

Facies	Temperature	Salinity
1. 12 m.—80-100 m. (Subfacies boundary at 30-50 m.)	(15 m.) 18-31°C.[*] (average) (50 m.) 20-26°C. (100 m.) 17-21°C.	Mississippi Delta 24 o/oo Mobile Bay 34 o/oo West Coast Florida 36 o/oo
2. 80-100 m.—130-150 m.	16-21°C.	36 o/oo
3. 130-150 m.—180-220 m.	(130 m.) 18-20°C. (200 m.) 13-15°C.	36 o/oo (or slightly higher)
4. 180-220 m.—350-600 m. (Subfacies boundary at 250 m.)	(200 m.) 13-15°C. (500 m.) 8-10°C.	35-36 o/oo
5. 350-600 m.—900-1000 m.	(500 m.) 8-10°C. (1000 m.) 5°C.	35 o/oo
6. 900-1000 m.—?	5°C.	35 o/oo

Table 1. Temperature and salinity in Facies 1-6 (These figures are approximations and refer in all cases to open-sea conditions).

Facies 1. 12 m.—80-100 m.

The inner margin of this facies represents an open-ocean condition. In no case does a traverse extend into a bay at its inner end, although common bay forms such as "*Rotalia*" *beccarii* variants often are found in great abundance at the inner ends of various traverses.

The following species are found in facies 1 only:

Elphidium advenum
Globulina caribaea
Guttulina australis
Nouria polymorphinoides
N. sp.
Quinqueloculina bicostata (in most cases)
Q. sabulosa

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[*] Minimum temperature near Mobile Bay and from Cedar Keys southward is 21°C. Maximum temperatures may be somewhat lower east of the Mississippi Delta.

The following species are found in fairly high concentration in this facies only:

Ammoscalaria pseudospiralis
(also facies 2, in traverse I)
Asterigerina carinata
Bigenerina irregularis
B. textularioidea
Buliminella cf. *bassendorfensis*
Cibicidina strattoni
"*Discorbis*" *bulbosa*
Elphidium discoidale
E. gunteri
E. poeyanum
Epistominella vitrea
Eponides antillarum
Nodobaculariella cassis
Nonionella opima
Peneroplidae
Planulina exorna
Rosalina cf. *concinna*
R. floridana
"*Rotalia*" *beccarii* variants
Textularia earlandi
T. mayori
Virgulina punctata

The following species also may be found occurring in this facies including the shoalest stations:

Amphistegina spp.
Angulogerina bella
A. jamaicensis
Bolivina albatrossi
B. barbata
B. lowmani
B. striatula spinata
Buccella hannai
Bulimina marginata
Cancris oblonga (and *C. sagra*)
Cassidulina subglobosa
Cibicides deprimus
C. protuberans
Elphidium spp. (exclusive of
named species)
Eponides repandus
E. turgidus
Gypsina vesicularis
Lagena spp. and related forms
Nonionella atlantica
Planorbulina mediterranensis
Pyrgo murrhina (rare)
P. cf. *nasutus*
Quinqueloculina compta
Q. horrida
Q. lamarckiana
Rectobolivina advena
Reussella atlantica
Robulus spp.
Rosalina parkerae
R. suezensis
Sigmoilina sp.
Spirillina vivipara
Spiroloculina cf. *grata*
S. soldanii
Stetsonia minuta
Textularia candeiana
T. conica
Triloculina cf. *brevidentata*
Uvigerina parvula
Virgulina complanata
V. pontoni
Wiesnerella auriculata

The following species have their shoalest occurrences between 35 and 50 m. and mark the boundary of what is considered here a subfacies:

Alveolophragmium sp.
Bolivina fragilis
B. subaenariensis mexicana
B. subspinescens
Bulimina aculeata
Cassidulina carinata
C. curvata
C. laevigata
Cibicides aff. *floridanus*
C. io
C. mollis
C. umbonatus
Conorbina orbicularis
Gaudryina cf. *aequa*
Goësella mississippiensis (starts at 70 m.)
Lenticulina peregrina
Loxostomum abruptum
Marginulina marginulinoides
Proteonina diffiugiformis
Pseudoeponides umbonatus
Reophax hispidulus
R. irregularis
Rosalina bertheloti
R. floridensis
Seabrookia earlandi
Sigmoilina distorta
Siphonina bradyana
S. pulchra
Spiroplectammina floridana
Textulariella spp.
Trifarina bradyi
Valvulineria minuta

There is considerable change laterally in facies 1. The following are species occurring in this facies, in one or more traverses, with a frequency of 10 per cent or more. They are not necessarily confined to this facies and may be found also in facies 1 at lower frequencies in other traverses.

	Traverse
Ammoscalaria pseudospiralis	I, IV
Amphistegina spp.	VI
Asterigerina carinata	VI-VIII
Buliminella cf. *bassendorfensis*	III
Cibicidina strattoni	IV-VII
Epistominella vitrea	III
Goësella mississippiensis	I
Miliolidae	VII
Nonionella atlantica	IV
N. opima	III, IV
Nouria sp.	I-III
Planulina exorna	V-VIII
Peneroplidae	VI, VIII
Rosalina cf. *concinna*	IV-VIII
''*Rotalia*'' *beccarii* variants	II, IV, VI
Textularia earlandi	I-III

It is probable that on the continental shelf along the Florida coast there is a further influx of West Indian forms such as are found in the Dry Tortugas. As can be seen from the above list, the fauna typical of calcareous areas is well established as far west as traverse VI, characterized by the abundance of *Amphistegina, Asterigerina carinata,* and the Peneroplidae. These forms are present, however, as far west as traverse IV.

Facies 1 is found in the various traverses as follows: traverse I, sta. 208-211 (51-73 m.); II, sta. 16-18 (33-88 m.); III, sta. 25-28 (22-106 m.); IV, all stations (20-62 m.); subfacies starts at sta. 221 (35 m.); V, sta. 77-97 (20-75 m.), subfacies starts at sta. 78 (71 m.); VI, sta. 59-73 (20-91 m.), subfacies starts at sta. 66 (39 m.); VII, sta. 174-177 (22-49 m.), subfacies starts at sta. 176 (46 m.); VIII, sta. 156-172 (12-62 m.), subfacies starts at sta. 161 (35 m.). The facies is not represented in traverses IX-XI.

Facies 2. 80-100 m. — 130-150 m.

The following species have their shoalest occurrence at 80-100 m.:

Ammobaculites sp. A.
Bolivina ordinaria
Cassidulina neocarinata
Cibicides corpulentus
  (starts at 120 m.)
Gaudryina (*Pseudogaudryina*) *atlantica*
Globobulimina mississippiensis
Haplophragmoides bradyi
Höglundina elegans
Liebusella spp.
Nonion formosum
Pseudoclavulina mexicana
P. aff. *novangliae*
Planulina foveolata
Pullenia quinqueloba
Robertina bradyi
"*Rotalia*" *translucens*
Rotamorphina laevigata
Sphaeroidina bulloides
Textularia foliacea occidentalis
Trochammina quadriloba
Uvigerina flintii
U. laevis
Virgulina mexicana

The following species have their deepest occurrence at 130-150 m.:

Conorbina orbicularis (160 m.)
Elphidium poeyanum
Eponides antillarum
Gaudryina cf. *aequa*
Gypsina vesicularis
Planorbulina mediterranensis
  (mostly)
Quinqueloculina bicostata
Q. compta
"*Rotalia*" *beccarii* variants

The following species occur only occasionally deeper than 150 m.:

Cassidulina laevigata
Cibicides io
C. mollis
Eponides repandus
Nodobaculariella cassis
Rosalina floridensis
Spiroloculina cf. *grata*
Textularia conica
T. mayori

The following species are not found with frequencies greater than 1 per cent deeper than 150 m.:

Nonionella atlantica
Planulina exorna
Quinqueloculina lamarckiana
Reussella atlantica

There is a marked lateral change in this facies also. The following species are found with frequencies higher than 10 per cent in the various traverses. They are not necessarily confined, however, to facies 2.

	Traverse
Alveolophragmium sp.	I
Ammoscalaria pseudospiralis	I
Amphistegina spp.	VII, VIII
Cassidulina subglobosa	VI
Cibicides protuberans	VIII
Goësella mississippiensis	I, II
Miliolidae	VI (1 sta.)
Nouria sp.	I
Proteonina difflugiformis	I
Rosalina cf. *concinna*	VI, VII
Trochammina quadriloba	I

As can be seen from the above list, many of the species also are found in high frequencies in facies 1. The species having a high frequency in the Mississippi Delta region form a discrete group as they did in facies 1. Facies 2 does not appear in enough of the traverses to give a complete analysis of its lateral development.

Facies 2 is found in the various traverses as follows: traverse I, sta. 204-207 (79-91 m.); traverse II, sta. 19-21 (106-142 m.); traverse V, sta. 76 (99 m.); traverse VI, sta. 54-57 (106-128 m.); traverse VII, sta. 178, 179 (86-146 m.); traverse VIII, sta. 154, 155 (79-117 m.). It is not represented in traverses III, IV, IX-XI. No species are found with high frequencies in this facies in traverse V. As can be seen, facies 2 is not represented at many stations and it might be more practical in many cases to combine it with facies 3. It seems advisable, however, to give its characteristics for what they might be worth for faunal analysis even though the results may not be statistically valid.

Facies 3. 130-150 m. — 180-220 m.

The shoaler limit of this facies is marked by the following species having their shoalest occurrence at 130-150 m.:

Bolivina goësii
B. translucens
Bulimina spicata
Cassidulina aff. *crassa*
Chilostomella oolina (125 m.)
Eggerella bradyi
Eponides regularis
Globobulimina affinis and variant
Glomospira charoides
G. cf. *gordialis*
Gyroidina orbicularis (165 m.)
Gyroidinoides soldanii altiformis
Karreriella bradyi
Planulina ariminensis
Pseudoglandulina comatula
Pullenia bulloides
Sigmoilina tenuis
Trochammina advena

The following species have their deepest occurrence at 180-220 m.:

Alveolophragmium sp.
Ammoscalaria pseudospiralis
Asterigerina carinata
Bigenerina irregularis
B. textularioidea
Buccella hannai
Cibicides io
C. mollis
''Discorbis'' bulbosa
Elphidium discoidale
E. gunteri
Eponides repandus
Globobulimina mississippiensis
Goësella mississippiensis
(very occasionally deeper)
Quinqueloculina cf. *polygona*
Rectobolivina advena
Rosalina floridensis
Spirillina vivipara
Spiroplectammina floridensis
Wiesnerella auriculata

The following species do not occur deeper than 220 m. with a frequency greater than 1 per cent.

Bolivina striatula spinata
Reophax hispidulus
Rosalina cf. *concinna*
R. suezensis

Lateral changes are still marked in this facies. The following species occur with frequencies of more than 10 per cent. They are not necessarily limited to this facies.

	Traverse
Alveolophragmium sp.	I
Bolivina barbata	II, III
B. lowmani	VII
B. minima	VIII
B. subaenariensis mexicana	III, VI
Bulimina marginata	II
Cassidulina neocarinata	VI
Cibicides aff. *floridanus*	VII
C. protuberans	IX, XI
Eponides regularis	II
Goësella mississippiensis	I
Proteonina difflugiformis	I
Trochammina quadriloba	I, II
Uvigerina parvula	III, VII

The Mississippi Delta fauna is still prominent in this facies, to a greater extent in traverse I than in traverse II. High frequency occurrences appear to be rather spasmodic but this is probably emphasized by the choice of a definite frequency limit to indicate them.

Facies 3 is found in traverse I, sta. 202 (128 m.); traverse II, sta. 22 (168 m.); traverse III, sta. 29, 30 (155-205 m.); traverse V, sta. 75 (146 m.); traverse VI, sta. 50-53 (139-165 m.); traverse VII, sta. 180 (183 m.); traverse VIII, sta. 152, 153 (146-183 m.); traverse IX, sta. 138 (183 m.); traverse XI, sta. 116-118 (139-155 m.).

Facies 4. 180-220 m. — 350-600 m.

The deeper depth limit of this facies is not sharply defined, but between the depths of 350-600 m. very definite faunal differences occur, and the same is true to a much lesser extent at the shoaler depth limit. There is a less well-defined boundary at 250 m., also, so that the shoaler limit could be defined as 180-250 m. The faunal changes at 250 m. will be listed separately, however, as they appear to form a small but distinctive unit.

The following species have their shoalest occurrence at 180-220 m.:

Adercotryma glomeratum
Anomalinoides mexicana
Bulimina alazanensis
B. striata mexicana
Epistominella exigua
Gyroidina neosoldanii
Hormosina sp.
Laticarinina pauperata
Nodosaria hispida
Sigmoilina schlumbergeri
Trochammina cf. *japonica*
Uvigerina hispido-costata
U. peregrina

The following species have their shoalest occurrence at 250 m.:

Cassidulinoides tenuis
Cibicides robertsonianus
Epistominella rugosa
Loxostomum abruptum
Uvigerina auberiana

The following species have their deepest occurrence at 250 m. (exceptions noted):

Amphistegina spp.
Angulogerina bella
Bolivina fragilis
B. striatula spinata
Cancris oblonga
Cibicidina strattoni
Liebusella spp. (280 m.)
Nodobaculariella cassis
Pseudoglandulina comatula
Quinqueloculina lamarckiana (280 m.)
Reophax irregularis
Reussella atlantica
Sigmoilina sp.
Textularia conica (280 m.)
T. foliacea occidentalis
T. mayori
Triloculina cf. *brevidentata*

The following species have their deepest occurrence between 350 and 600 m.; a few having their deepest ranges shoaler or deeper also are noted:

Ammobaculites sp. A (390 m.)
Bolivina barbata (550 m.)
B. goësii (420 m.)
Bulimina marginata (550 m.)
Buliminella cf. *bassendorfensis* (370 m.)
Cassidulina laevigata (320 m.)
Marginulina marginulinoides (450 m.)
Nonionella atlantica (600 m.)
Planulina exorna (380 m.)
P. foveolata (550 m.)
Pseudoclavulina mexicana (450 m.)
P. aff. *novangliae* (350 m.)
Pyrgo cf. *nasutus* (550 m.)
Quinqueloculina horrida (370 m.)
Rosalina bertheloti (370 m.)
Sigmoilina distorta (550 m.)
Siphonina bradyana (650 m.)
S. pulchra (750 m.)
Spiroloculina cf. *grata* (650 m.)
S. soldanii (320 m.)
Textulariella spp. (320 m.)
Uvigerina flintii (420 m.)
Virgulina pontoni (500 m.)

The following species do not occur with a frequency greater than 1 per cent deeper than 600 m.:

Cassidulina aff. *crassa*
C. neocarinata
Eponides regularis
Planulina ariminensis
Uvigerina hispido-costata

The following species are found with frequencies greater than 10 per cent in the various traverses. Traverses I and II in the Mississippi Delta region still show differences from the more easterly ones:

	Traverse
Ammobaculites sp. A	I
Bolivina albatrossi	VI
B. minima	VIII
B. subaenariensis mexicana	V, VI
Bulimina marginata	II
B. striata mexicana	II
Cassidulina neocarinata	VII
C. subglobosa	IX
Epistominella rugosa	IX
Goësella mississippiensis	I, II
Proteonina difflugiformis	I, II
Reophax scorpiurus	II
''Rotalia'' translucens	VI-IX
Sphaeroidina bulloides	II
Textularia earlandi	I
Trochammina quadriloba	I, II
Uvigerina peregrina	II

Facies 4 is found in the various traverses as follows: traverse I, sta. 201, 203 (201-430 m.); traverse II, sta. 15, 23 (208-298 m.); traverse V, sta. 74, 99, 100 (204-530 m.); traverse VI, sta. 47-49 (183-446 m.); traverse VII, sta. 181-186 (186-347 m.); traverse VIII, sta. 151 (366 m.); traverse IX, sta. 140-142 (256-421 m.). The facies is not represented in traverses II, IV, X, XI.

Facies 5. 350-600 m. — 900-1000 m.

The deeper depth limit is well-defined, especially by the species having their shoalest occurrences at this point. These forms will be listed under facies 6. The species, with a few exceptions, having their shoalest occurrence between the depths of 350 m. and 600 m. are as follows:

Astrononion tumidum (320 m.)
Bolivina sp. (420 m.)
Cibicides kullenbergi (600 m.)
C. rugosa (600 m.)
C. wuellerstorfi (450 m.)
Cyclammina spp. (380 m.)
Eponides polius (600 m.)
Osangularia cultur (400 m.)
Plectina apicularis (550 m. mostly)
Quinqueloculina sp. (600 m.)
Rectobolivina dimorpha (350 m.)
Tolypammina schaudinni (550 m.)
Virgulina tessellata (360 m.)

The following species have their deepest occurrence at 900-1000 m.:

Rosalina floridana
R. suezensis
Textularia earlandi
Uvigerina hispido-costata
U. parvula

The following species do not occur with a frequency greater than 1 per cent deeper than 900-1000 m.:

Bolivina minima
E. ordinaria
Chilostomella oolina
Sphaeroidina bulloides
Trifarina bradyi

Traverse I did not penetrate this facies. The indications are, however, that there is more uniformity from east to west in this facies than in the shoaler ones. The following species have a frequency greater than 10 per cent in the various traverses in facies 5:

	Traverse
Bolivina albatrossi	II, III
B. ordinaria	II, III, VI
Bulimina aculeata	III, V
B. alazanensis	V, VI, IX
Cassidulina carinata	III
C. subglobosa	VI-VIII, XI
Epistominella exigua	II, VI, VII, IX
"Rotalia" translucens	VI-VIII
Sphaeroidina bulloides	II
Trochammina cf. *japonica*	II
T. tasmanica	II
Uvigerina laevis	II
U. peregrina	V, VI, VIII, IX

This facies is represented in the various traverses as follows: traverse II, sta. 12-14, 24 (314-732 m.); traverse III, sta. 31, 32 (373-400 m.); traverse V, sta. 101 (914 m.); traverse VI, sta. 40-46 (555-960 m.); traverse VII, sta. 187-190 (457-878 m.); traverse VIII, sta. 149, 150 (585-914 m.); traverse IX, sta. 144 (914 m.); traverse XI, sta. 124 (914 m.). The facies is not represented in traverses I, IV, X.

Facies 6. 900-1000 m. — ?

There is no marked facies boundary deeper than 900-1000 m. in this area. Several species appear or drop out deeper, however, before the greatest depth represented by these samples is reached at 3283 m.

The species having their shoalest occurrence at 900-1000 m. are as follows:

Alveolophragmium ringens (mostly)
Ammobaculites sp. B.
Ammoscalaria tenuimargo
Epistominella decorata
Gaudryina flintii
Pullenia sp.
Siphotextularia curta
S. rolshauseni
Tolypammina schaudinni (mostly)
Trochammina globulosa

Species having their shoalest occurrence deeper than the above are as follows:

Bolivina pusilla (1300 m., a few exceptions shoaler)
Nonion pompilioides (2250 m.)
Quinqueloculina venusta (1800 m.)
Reophax distans delicatulus (1200 m.)
Virgulina advena (1250 m.)

The following species have their deepest occurrence between 1000 m. and 3000 m.:

Alveolophragmium ringens (2400 m.)
A. wiesneri (1700 m.)
Angulogerina jamaicensis (1700 m.)
Anomalinoides mexicana (1700 m.)
Astrononion tumidum (2600 m.)
Bolivina ordinaria (2200 m.)
Chilostomella oolina (2900 m.)
Cibicides corpulentus (1700 m.)
C. deprimus (2500 m.)
C. aff. *floridanus* (1700 m.)
C. protuberans (1800 m.)
C. rugosa (2700 m.)
"Discorbis" bulbosa (2200 m.)
Epistominella vitrea (2300 m.)
Eponides regularis (1900 m. mostly)
Gaudryina flintii (2300 m.) (confined to facies 6)
Hormosina sp. (1900 m.)
Nonion formosum (1800 m.)
Nonionella opima (2300 m.)
Nummoloculina irregularis (2500 m.)
Planulina ariminensis (2500 m.)
Rectobolivina dimorpha (1400 m.)
Robertina bradyi (2600 m.)
Robulus spp. (2200 m.)
Sigmoilina tenuis (1700 m.)
Siphotextularia curta (2700 m.)
Virgulina punctata (2500 m.)
V. tessellata (2200 m.)

Facies 6 is fairly uniform throughout the area. The following species occur with a frequency of greater than 10 per cent in the various traverses:

	Traverse
Bolivina albatrossi	III (1 sta.)
Bulimina aculeata	II, III (not deeper than 1500 m.)
B. alazanensis	X (not deeper than 1100 m.)
B. spicata	X (not deeper than 1000 m.)
Cassidulina subglobosa	VI, VIII-XI
Cibicides wuellerstorfi	II, VII-XI (deeper than 2400 m.)
Epistominella decorata	II, III, V-VII, IX, X (deeper than 1400 m.)
Eponides turgidus	II, III, V, VI
Glomospira charoides	X (1 sta.)
Höglundina elegans	IX, X (1 sta. each)
Reophax distans delicatulus	III (1 sta.)
Uvigerina peregrina	II, V, VI (not deeper than 1500 m.)
Virgulina tessellata	III (not deeper than 1500 m.)

This facies is represented in the various traverses as follows: traverse II, sta. 3-11 (914-3017 m.); traverse III, sta. 33-37 (1024-2388 m.); traverse V, sta. 102-105 (1097-1417 m.); traverse VI, sta. 38, 39, 106 (1144-2697 m.); traverse VII, sta. 191, 107 (2999-3017 m.); traverse VIII, sta. 146, 148 (1730-3164 m.); traverse IX, sta. 108, 137, 145 (2268-3072 m.); traverse X, all stations (1051-2150 m.); traverse XI, sta. 1, 2, 110-113, 120-123 (1326-3283 m.). The facies is not represented in traverses I and IV.

LATERAL CHANGES IN FAUNAS

A study of the species forming the bulk of the faunas in the various facies in each traverse shows very clearly that there is a lateral change in faunas in this area. The traverses off the Mississippi Delta contain faunas which differ from those on both sides. Such species as *Goësella mississippiensis* n. sp. and *Textularia earlandi* are restricted to this region. This is probably due to the outflow of the Mississippi River which would affect the turbidity, light penetration, food supply and the chemistry of the water and sediments. The salinity is not affected very much except at the shoalest stations and probably is not a controlling factor.

Eastward from the Mississippi Delta there is an increase on the continental shelf and out to depths of 100-200 m. of West Indian species: *Asterigerina carinata*, various species of the Peneroplidae, *Amphistegina*, etc. These forms are well established as far west as traverse VI. They are not found in the northwestern Gulf of Mexico except on isloated reefs. A study of the Foraminifera in samples from the continental shelf east of the Mississippi Delta, which extends to a depth of about 75 m., shows that except for a few stations at the inner ends of the traverses the area is apparently non-depositional. The sediment is mostly gravel, sand, and shells and there is no material present which could produce turbid conditions. The sediment at the inner ends of traverses V-VIII usually is pure, coarse quartz sand. A large percentage of the Foraminifera in this non-depositional area is worn and discolored and many are filled with glauconite. The relative abundance, therefore, of such robust forms as *Amphistegina,* the Peneroplidae, Miliolidae, etc. may be due in part to their survival over long periods of time where other more delicate forms are not preserved. Short cores could not be obtained from this material and the samples were not treated with formalin to preserve the living forms. A study of these would give more definite information concerning the present-day fauna.

Although there are no samples from the continental shelf along the west coast of Florida, the few relatively shallow samples show a further increase of West Indian forms. Many of these occur so rarely that they have not been included in the population counts but a few of them are listed in a subsequent section.

It is interesting that although lateral differences in the shoaler facies are marked for the bulk of the population, the facies boundaries can be identified easily throughout the area, in many cases by the same species. In progressively deeper facies the lateral changes disappear to a great extent and deeper than 1000 m. the faunas are fairly uniform.

DISTRIBUTION OF LIVING BENTHONIC SPECIES

The living forms were studied in samples which were collected with the Phleger sampler (listed in Table 3). These extend over most of the area except that shoaler than 75 m. in traverses V-VIII and the few shoal stations in traverses X and XI. The absence of data for these stations makes it impossible to give a complete picture of the occurrence of living specimens in the area but the data obtained are given in Tables 25-28 so that they may be on file for study when additional work may supplement them. These tables list numbers of specimens of each species found in 10 cc. of sediment, the surface area covered being about 5 sq. cm., half the surface area sampled.

Population counts of living Foraminifera were made of all the samples in traverses I-IV and some interesting results were obtained. Phleger (1951, p. 65) has pointed out that relative rates of sedimentation may be estimated by comparing numbers of living forms present relative to the dead population. A decrease in the relative numbers of living specimens would indicate a decrease in the sedimentation rate since the dead population would not be so rapidly masked by sedimentation. Living populations expressed as percentages of total population (living and dead) for traverses I-IV are listed in Table 2. There is evidence in a few of the shoaler samples of decalcification of some of the specimens possibly due to the increasing acidity of the samples after collection. This is detected by the presence of casts composed of stained protoplasm. In such cases the percentages of living populations given are probably higher than they should be.

A study of Table 2 shows that in traverse I the living population in percentage of total population ranges from 68 at 51 m. to 7 at 430 m.; in traverse II it ranges from 100 per cent at 33 m. to 0 per cent at 3017 m. Living populations fall to 4 per cent at 314 m. and are very low, usually less than 1 per cent, deeper. The sample containing 100 per cent living specimens showed evidence of decalcification. In traverse III the percentage is 83 at 22 m., varies from 2-11 to a depth of 1719 m., and drops below 1 at 2388 m. In traverse IV, with all stations at depths shoaler than 62 m., the percentages are less than 1 at the Mobile Bay end (with the exception of sta. 217 which shows anomalous characteristics), remaining so southward to sta. 215 which has 3, sta. 214, 5, sta. 213, 40, and sta. 212, 18 per cent. These figures bear out the fact that in the vicinity of the Mississippi Delta sedimentation is more rapid than in the area to the northeast or at the deeper

Traverse I			Traverse II			Traverse III			Traverse IV		
Sta.	Depth in Meters	% Living	Sta	Depth in Meters	% Living	Sta	Depth in Meters	% Living	Sta.	Depth in Meters	% Living
211	51	68	16	33	100	25	22	83	225	20	0.4
210	86?	18	17	58	25	26	53	2	224	20	0.5
209	86?	6	18	88	8	27	77	2	222	33	0.1
208	73	15	19	106	0.4	28	106	11	221	35	0.2
207	82	17	20	113	3	29	155	8	220	37	0.5
206	79	8	21	142	10	30	205	8	219	38	1
205	82	7	22	168	3	31	373	2	218	42	0.3
204	91	11	23	208	5	32	400	2	217	40	24
202	128	12	15	298	0.4	33	1024	2	216	42	0.2
203	201	6	24	314	4	34	1262	6	215	47	3
201	430	7	14	471	0	35	1481	6	214	49	5
			13	631	2	36	1719	2	213	55	40
			12	732	0.2	37	2388	0.3	212	62	18
			11	914	2						
			10	1298	0.3						
			9	1372	0.5						
			8	1417	1						
			7	1875	0.6						
			6	2468	0.2						
			5	2788	2						
			4	2972	0						
			3	3017	0						

Table 2. Living benthonic population, in percentage of total benthonic population, in traverses I-IV.

stations to the south. There are insufficient data to draw any further conclusions, but the inference is clear that with sufficient data much could be learned about sedimentation rates by this means.

To a depth of 200 m. most of the species present in significant frequencies have living representatives; deeper than this the representation by living forms is spasmodic and they usually form less than 1 per cent of the total population. The various species of *Reophax* are an exception to the general rule. They are usually represented by a relatively large number of living specimens. This is especially true of *R. hispidulus.* The relatively large number of living specimens of these species and the low frequency of dead specimens suggests that these forms usually are destroyed soon after death. The tests of *R. hispidulus* are very fragile, the sand grains which form them being weakly cemented, so that once the supporting protoplasm is gone the specimens probably disintegrate rapidly. The same observation was made of such arenaceous species, in the shoal samples in the Mississippi Delta region, as *Goësella mississippiensis* n. sp., *Nouria polymorphinoides* and *Nouria* sp. Such fragile forms seldom appear in fossil assemblages and are probably not present in modern dead assemblages in the frequencies warranted by their actual rate of production.

DISTRIBUTION OF PLANKTONIC SPECIES (LIVING AND DEAD)

The relative distributions of the planktonic species are very similar throughout the area. Table 24 gives the percentage distributions in traverse VII and these may be taken, with some variation, as representative of the entire area. The total numbers of planktonic specimens in each sample are given in Tables 4-23. The species are not figured in the present report; the figures given by Phleger *et al* (1953) illustrate most of them and are accompanied by full taxonomic notes. The following species occur in the area:

Candeina nitida d'Orbigny
Globigerina bulloides d'Orbigny
G. digitata H. B. Brady
G. eggeri Rhumbler
G. inflata d'Orbigny
G. pachyderma (Ehrenberg)
G. sp.
Globigerinella aequilateralis (H. B. Brady)
Globigerinita glutinata (Egger)
Globigerinoides conglobata (H. B. Brady)
G. rubra (d'Orbigny)
G. sacculifera (H. B. Brady)
Globorotalia hirsuta (d'Orbigny) (4 occurrences)
G. menardii (d'Orbigny)
G. punctulata (d'Orbigny)
G. scitula (H. B. Brady)
G. truncatulinoides (d'Orbigny)
G. tumida (H. B. Brady)
Hastigerina pelagica (d'Orbigny)
Orbulina universa d'Orbigny
Pulleniatina obliquiloculata (Parker and Jones)
Sphaeroidinella dehiscens (Parker and Jones)

The species listed as *Globigerina* sp. is a small form with a maximum diameter of 0.25 mm. It is apparently identical to that referred by Rhumbler (1911, pl. 30, figs. 1-6) to *G. lamellosa*

Terquem. It is probably not this Eocene species which is later referred by Le Calvez (1949, p. 17) to "*Discorbis propinqua*" (Terquem). *Globigerina* sp. has a thin supplementary chamber extending from the dorsal side between the last-formed chamber and the first one in the last-formed whorl, to varying degrees over the umbilicus. There are supplementary apertures along the sides of this chamber which in many respects is similar to the supplementary chambers of *Globigerinita*. This chamber is apparently resorbed or destroyed when new regular chambers are added since there is no trace of previous ones. The species in other respects resembles a *Globigerina* of the *G. quinqueloba* Natland type. It is probable that it represents a new genus.

Globigerinita glutinata occurs in the area in some abundance. A re-examination of samples from the northwestern Gulf of Mexico shows that it is present there also although it is not reported by Phleger and Parker (1951).

The planktonic species appearing in the highest frequencies are (in order of abundance):

Globigerinoides rubra
Globigerina bulloides
G. eggeri
Globigerinoides sacculifera
Globorotalia truncatulinoides
G. menardii
Pulleniatina obliquiloculata
Globigerinita glutinata
Globigerinella aequilateralis

This assemblage of high-frequency species combines elements typical of both mid- and low-latitude faunas in the North Atlantic (Phleger *et al,* 1953). *Globigerina bulloides* and *Globorotalia truncatulinoides* are present in higher frequencies than they appeared in North Atlantic low latitudes although they are not quite so high as in the mid-latitudes. Conversely, *Globigerina eggeri, Globigerinoides sacculifera* and *Globorotalia menardii* are present in higher frequencies than they appeared in mid-latitudes but not so high as in the low. *Pulleniatina obliquiloculata* is present at frequencies characteristic of low latitudes. The remaining species are not diagnostic.

Of the rarer species, *Globigerina inflata* and *G. pachyderma* are diagnostic of mid-latitudes. *Globorotalia scitula* is present at mid-latitude frequencies. *G. tumida* is present at somewhat higher frequencies than are typical of mid-latitudes but less than those of low latitudes.

As stated previously, surface temperatures in the Gulf of Mexico range from an average minimum of 20°C. in February to an average maximum of 29°C. in August. The average maximum of 29°C. is higher than any found in the North Atlantic, except locally, even in the equatorial region. The minimum of 20°C. is comparable to that found between N Lat. 30° and 35° in the North Atlantic. There, the average maximum temperatures range from 26.5-27.5°C. In respect to temperature, then, the Gulf of Mexico combines the minimum of the North Atlantic mid-latitudes with a maximum in excess of that found in North Atlantic low latitudes. This may in part explain the anomalies of the planktonic assemblage found in the eastern Gulf of Mexico.

It is easy to explain the introduction of planktonic species which occur in low latitudes into the Gulf of Mexico by the surface current flowing north from the Caribbean Sea. The presence of *Globigerina inflata* and *G. pachyderma* (and possibly *Globorotalia hirsuta, G. punctulata* and *G. scitula*) are more difficult to explain since they apparently do not occur in the Caribbean nor are they found in the western part of the Gulf of Mexico. It is postulated that these species may be introduced from the Atlantic by a shallow coastal current flowing from east to west along the Florida coast. R. C. Reid (personal communication) says that it is very possible that such a current exists and that the conformation of the Florida Keys strongly suggests it. The circulation in the gulf itself being divided into two main eddies in the eastern and western parts probably would explain why *Globigerina inflata* and *G. pachyderma,* which are rare, appear only in the eastern Gulf of Mexico area.

The total number of planktonic specimens in the samples is very variable. In the Mississippi Delta region they do not occur in the sediments as shoal as in the rest of the area and are almost completely absent in traverse I to a depth of 430 m. In traverse II they occur at 88 m. but not significantly until considerably deeper and in traverses III-VIII in small numbers shoaler than 50 m. Their absence in the delta region is probably due to the outflow of the Mississippi River which causes water to flow out over the surface for long distances. Throughout the area samples taken at less than 100 m. usually contain planktonic specimens at less than 10 per cent of total population. Deeper than 1000 m.

they usually compose 90 per cent or more of the total population.

Deeper than about 150 m. the planktonic specimens at many stations show evidence of solution of the tests. This is shown especially by the large number of broken specimens. At some stations at least 50 per cent of the fauna appears to be affected. Since it is unknown how rapidly fresh tests are added, it is impossible to tell how rapidly solution takes place. The relatively small number of fresh specimens at some deep-water localities suggests that solution is fairly rapid.

Tables 29 and 30 list the number of living specimens of planktonic species found at the various stations. Since protoplasm is rapidly destroyed after death, probably not remaining in the test more than 12-14 hours, the specimens very likely represent actual living forms which for some reason have fallen to the bottom and survived. There are more living representatives of the abundant species than the rare ones. This implies that the living forms do not necessarily represent selected species which may have benthonic stages. Such rare species as *Globigerina inflata, Globigerinoides conglobata, Sphaeroidinella dehiscens,* etc. have no living representatives.

BENTHONIC SPECIES

Introduction

Two hundred and five benthonic species and thirteen generic or family groups have been used in compiling the data of the present report, including ten new species and one new genus. These constitute only a part of the fauna but are a large proportion of the total population. The remainder of the fauna is present in small quantities and for the most part the species have no distributional significance. Some of the species in this group which appear to have limited depth ranges are:

	Depth	Traverse
Buliminella elegantissima (d'Orbigny)	to 140 m.	IV-VIII
Cassidulina norcrossi australis Phleger & Parker	140-585 m.	VI-VIII
C. palmerae Bermudez and Acosta	135-255 m.	IX-XI
Cassidulinoides bradyi (Norman)	140-375 m.	scattered

	Depth	Traverse
Chrysalidinella sp.	to 155 m.	scattered
Cornuspira planorbis Schultze	to 185 m. (mostly)	scattered
Dorothia caribaea Cushman	140-155 m.	VI, VII, XI
Ehrenbergina undulata Parker	320-450 m. (mostly)	VI-X
Gaudryina antillana Bermudez and Acosta	85-180 m.	VI-IX
Patellina corrugata Williamson	to 240 m. (mostly) rare to 1300 m.	scattered
Siphotextularia subplana (Cushman)	115-255 m.	scattered
Stomatorbina concentrica (Parker and Jones)	55-185 m.	VI-IX, XI
Textularia mexicana Cushman	135-370 m.	VI-VIII
Uvigerina sp. (hirsute with undercut chambers)	deeper than 1550 m.	VI, IX-XI

There has been little previous work in this area. Flint (1899) and Cushman (1918-1931) report on samples collected by the U. S. Bureau of Fisheries ship ALBATROSS. Most of this material is from deep water stations. Lowman (1949, 1951) gives data on the distribution of genera off Pensacola and Choctawhatchee Bay, Florida.

About 75 per cent of the present fauna is reported by Phleger and Parker (1951) in the northwestern Gulf of Mexico. About 15 per cent of the species reported by them are not present or occur only rarely in the eastern area. There is an increase east of Mobile Bay in the number of species characteristic of the West Indian region, but many of the West Indian species found on the isolated reefs of the northwestern Gulf of Mexico are not present in the northeastern. It is possible that they may be found in shallow areas along the Florida coast not included in this report since many of them are reported from the Tortugas region by Cushman (1922). A few deep-water species characteristic of the North Atlantic, such as *Cibicides kullenbergi* and *Bolivina pusilla,* occur in the northeastern area but not in the northwestern.

Under each species details of depth and areal distribution are given. Cushman's classification is used for convenience although the writer is not in complete agreement with it. Figured specimens are deposited in the U. S. National Museum, Washington, D. C.

Discussion of Species

Family SACCAMMINIDAE

Under "Saccamminidae and related forms" in the population counts are included various single-chambered forms which could not be readily differentiated in counting. Probably included here are specimens of *Reophax* and *Hormosina* represented by single chambers. The group is included in the counts because in some cases it forms a large component of the fauna.

These forms have an overall depth range from 125 m. to 2700 m. In traverse II they occur with frequencies of 5-20 per cent from 140 m. to 170 m.; 1-5 per cent to a depth of 1400 m. In the remaining traverses the occurrence is scattered.

PROTEONINA ATLANTICA Cushman

(Plate 1, figure 1)

Proteonina atlantica Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 5, pl. 1, fig. 4.

This species was combined with the following one by Phleger and Parker (1951). As I have previously pointed out (Parker, 1952, p. 393) the two species are very distinct.

P. atlantica has a sccattered occurrence in traverses II, IV-VII, usually less than 1 per cent. In traverse IV it occurs with a frequency of 20 per cent and 48 per cent at two stations shoaler than 60 m. These two stations, however, showed a relatively small arenaceous fauna in which calcareous forms may have been destroyed by decalcification. Most occurrences are shoaler than 500 m. but there are a few between 1000 and 3000 m., mostly with frequencies between 1-5 per cent.

PROTEONINA DIFFLUGIFORMIS (H. B. Brady)

(Plate 1, figure 2)

Reophax difflugiformis H. B. Brady, 1879, Quart. Journ. Micr. Sci., vol. 19, p. 51, pl. 4, figs. 3a, b.

This species occurs in all traverses except IV. It is found at all depths. Frequencies of 6-10 per cent are found in traverse I from 70-200 m., and in traverse II from 1450-1700 m.; elsewhere they are less than 6 per cent.

Family REOPHACIDAE

REOPHAX BILOCULARIS Flint

(Plate 1, figure 3)

Reophax bilocularis Flint, 1899, Rept. U. S. Nat. Mus., (1897), p. 273, pl. 17, fig. 2.

Three-chambered specimens occur frequently but the third chamber is relatively very small.

This species occurs in all traverses except I and IV, in most cases with a frequency of less than 1 per cent. In traverses II, III, V, it occurs deeper than 1000 m.; in VI-XI deeper than 320 m.

REOPHAX DISTANS DELICATULUS Cushman

(Plate 1, figure 4)

Reophax distans H. B. Brady, var. *delicatulus* Cushman, 1920, Bull. U. S. Nat. Mus., vol. 104, pt. 2, p. 13, pl. 4, fig. 2.

Cushman's figured specimen has a length (exclusive of the connecting necks) of 0.33 mm. but the maximum length of specimens found in the present study is 0.65 mm. Due to the fragility of the necks only single chambers occur. It is possible that small specimens without necks have been included in the population counts under Saccamminidae, etc. so that the distribution given below may not show the complete occurrence of the species.

The species occurs in all traverses but I and IV deeper than 1200 m., at less than 6 per cent except at the outer ends of traverses II and III where it is 6 per cent and 12 per cent respectively.

REOPHAX GRACILIS (Kiaer)

Nodulina gracilis Kiaer, 1900, Rep't. Norwegian Fish Mar. Invest., vol. 1, no. 7, p. 24, text fig. 2 (1?).

This species occurs at 5 stations in traverses I, II, and IV between 47 m. and 430 m. Only living specimens were found. The fragility of the test makes survival in dried samples very unlikely.

REOPHAX GUTTIFERA H. B. Brady

(Plate 1, figure 5)

Reophax guttifera H. B. Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, p. 49; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 295, pl. 31, figs. 10-15.

This species has a scattered occurrence mostly at less than 1 per cent except in traverse II where it varies between 1 and 3 per cent from 300 m. to 914 m.

REOPHAX HISPIDULUS Cushman

(Plate 1, figures 6, 7)

Reophax hispidulus Cushman, 1920, Bull. U. S. Nat. Mus., vol. 104, pt. 2, p. 24, pl. 5, fig. 7.

The specimens appear to be identical with Cushman's species although they are less than 1 mm. in length whereas Cushman's exceed 3 mm. in length. Judging from the relatively large number of living specimens found, and the extreme fragility of the tests, it is probable that the figures shown in the total population counts are much lower than they should be. Very often living specimens are found when there are no empty tests in the dried samples.

The species occurs in all traverses but IV and IX, with frequencies ranging up to 3 per cent, at 45-3250 m.

REOPHAX IRREGULARIS n. sp.

(Plate 1, figures 9, 10)

Test medium in size; chambers not more than five in number, usually less, the initial one spherical, the remaining ones compressed with adjacent ones frequently set at an angle to each other, increasing in size as added; sutures depressed, often obscured by large fragments of wall material; wall rough, composed of sand grains, fragments of shell, etc. of varying sizes very irregularly cemented together. Maximum length of paratypes 1.7 mm.; width 0.6 mm. (not including projecting wall fragments).

Holotype from station 59, Lat. 29°58′ N, Long. 86°37′ W, at a depth of 91 m.

This species somewhat resembles *R. nothi* McFadyen but the wall of the test is much more irregular, the chambers do not increase so rapidly in size as added, and adjacent ones are often irregularly placed.

It occurs in traverses V-IX, XI, at depths of less than 185 m. except in IX where it is found to a depth of 255 m. Frequencies are below 6 per cent.

REOPHAX SCORPIURUS Montfort

(Plate 1, figure 11)

Reophax scorpiurus Montfort, 1808, Conch. Syst. Class. Meth. Coqu., p. 331, text fig. (p. 330).

This species occurs mostly in traverses I-III, with irregular occurrences elsewhere, to a depth of 400 m. Most deeper occurrences are at depths greater than 2600 m. Frequencies are less than 1 per cent except in traverses I and II where they range up to 5 per cent with one occurrence of 10 per cent at 208 m.

REOPHAX sp.

(Plate 1, figure 12)

This species is present in the form of isolated single chambers due apparently to weakness at the point of joining of the chambers. The maximum length of these chambers is 1.23 mm., width 0.2 mm. They are flask-shaped with the widest point below the middle.

Most occurrences are in traverse II from 315 m. to 735 m. Frequencies are below 6 per cent except for one occurrence of 10 per cent at 208 m.

HORMOSINA sp.

(Plate 1, figure 8)

This species occurs in traverses I-III, V-VII with frequencies of less than 1 per cent from 215-300 m. and 1750-1850 m. Frequencies are 1-5 per cent between 300 m. and 1750 m. There is one occurrence of 11 per cent in traverse I at 430 m.

Family AMMODISCIDAE

AMMODISCUS spp.

Species of this genus are grouped together owing to the lack of sufficient material for their proper analysis. Specimens occur in all traverses except IV usually with a frequency of less than 1 per cent, except in I where frequencies of 1-5 per cent are found at 128 m. and 201 m.

GLOMOSPIRA CHAROIDES (Jones and Parker)

(Plate 1, figure 14)

Trochammina squamata var. *charoides* Jones and Parker, 1860, Quart. Journ. Geol. Soc. London, vol. 16, p. 304.

This species occurs in all traverses but IV deeper than 130 m. at frequencies of less than 6 per cent in most cases. Higher frequencies up to 10 per cent occur in some areas deeper than 900 m.

GLOMOSPIRA cf. GORDIALIS (Jones and Parker)

(Plate 1, figure 13)

Trochammina squamata var. *gordialis* Jones and Parker, 1860, Quart. Journ. Geol. Soc. London, vol. 16, p. 304.

Trochammina gordialis Jones and Parker, Carpenter, Parker and Jones, 1862, Introd. Form. p. 141, pl. 11, fig. 4.

The specimens have a smooth, polished test and are questionably comparable to Jones and Parker's species.

The species has a scattered occurrence in the whole area deeper than 140 m. Frequencies are usually less than 1 per cent, occasionally higher.

TOLYPAMMINA SCHAUDINNI Rhumbler

(Plate 1, figure 15)

Tolypammina schaudinni Rhumbler, 1904, Archiv. Prot., vol. 3, pt. 1, p. 277, text fig. 126 (on p. 278).

Most occurrences are deeper than 914 m. with frequencies less than 6 per cent, in traverses II, III, VII-XI.

Family LITUOLIDAE

HAPLOPHRAGMOIDES BRADYI (Robertson)

(Plate 1, figure 16)

Trochammina robertsoni H. B. Brady, 1887 (not *T. robertsoni* H. B. Brady, 1876), Journ. Roy. Micr. Soc., p. 893.

Trochammina bradyi Robertson, 1891, Ann. Mag. Nat. Hist., ser. 6, vol. 7, p. 388.

This species is found in all traverses except IV, with two exceptions deeper than 165 m. Frequencies are less than 1 per cent in most of the area but may be as high as 5 per cent deeper than 630 m.

ADERCOTRYMA GLOMERATUM (H. B. Brady)

(Plate 1, figure 18)

Lituola glomerata H. B. Brady, 1878, Ann. Mag. Nat. Hist., ser. 5, vol. 1, p. 433, pl. 20, figs. 1a-c.

Most specimens are larger and composed of coarser sand grains than those from the Gulf of Maine and the Arctic; in other respects they seem identical.

The species occurs in all traverses except IV with a scattered occurrence from 200-1000 m., and a more consistent distribution deeper. Frequencies are less than 1 per cent to 1000 m. and 1-5 per cent, in most cases, deeper.

ALVEOLOPHRAGMIUM NITIDUM (Goës)

(Plate 1, figure 17)

Haplophragmium nitidum Goës, 1896, Bull. Mus. Comp. Zool., vol. 29, p. 30, pl. 3, figs. 8, 9.

The writer is following the opinion given by Loeblich and Tappan (1953, p. 28) in the use of the name *Alveolophragmium* for the genus having an interio-areal aperture which is undivided and forms a lineal slit. Many specimens of various species of this genus have been observed but in none of them has the aperture been subdivided. It would appear, therefore, that the divided aperture is restricted in its occurrence and is probably a true generic feature, giving separate status to the genus *Cribrostomoides*.

A. nitidum is found in all traverses but IV, in most cases deeper than 300 m. Frequencies are usually less than 1 per cent but occasionally 1-5 per cent.

ALVEOLOPHRAGMIUM RINGENS (H. B. Brady)
(Plate 1, figure 19)

Trochammina ringens H. B. Brady, 1879, Quart. Journ. Micr. Sci., n.s., vol. 19, p. 57, pl. 5, fig. 12

This species is more involute than others of this genus and the aperture is placed farther from the chamber margin, but in essentials it appears to be referable to *Alveolophragmium*.

Occurrences are scattered, mostly deeper than 1200 m., with frequencies of less than 1 per cent.

ALVEOLOPHRAGMIUM SCITULUM (H. B. Brady)
(Plate 1, figures 20, 21)

Haplophragmium scitulum H. B. Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, p. 50; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 308, pl. 34, figs. 11-13.

Gulf of Mexico specimens have an interio-areal aperture and this feature is also plainly visible in the section figured by Brady (fig. 13). Adult specimens are rare.

The species has a scattered distribution from 90-2950 m. usually at less than 1 per cent, occasionally higher.

ALVEOLOPHRAGMIUM SUBGLOBOSUM (G. O. Sars)
(Plate 2, figures 1, 2)

Lituola subglobosa M. Sars, 1868 (1869), Forh. Vid. Selsk. Christiania, p. 250 (nomen nudum); G. O. Sars, 1872, *ibid.*, p. 253.

Haplophragmium latidorsatum H. B. Brady, 1884 (not *Nonionina latidorsatum* Bornemann, 1885), Rept. Voy. CHALLENGER, Zool. vol. 9, p. 307, pl. 34, figs. 7, 8, 10, 14 (?) (not fig. 9).

Haplophragmoides subglobosum (G. O. Sars) Cushman, 1910, Bull. U. S. Nat. Mus., vol. 71, pt. 2, p. 105, text figs. 162-164.

Juvenile specimens are more irregularly coiled than are the adults. The species appears to be intermediate between *Recurvoides* and *Alveolophragmium* but is more closely allied to the latter in adult specimens.

The distribution is very scattered deeper than 300 m. with most occurrences deeper than 900 m. Frequencies are in most cases less than 1 per cent.

ALVEOLOPHRAGMIUM WIESNERI (Parr)
(Plate 1, figure 23)

Labrospira wiesneri Parr, 1950, B. A. N. Z., Antarctic Res. Exped., 1929-1931, Repts., ser. B, vol. 5, pt. 6, p. 272, pl. 4, figs. 25, 26.

Labrospira arctica Parker, 1952, Bull. Mus. Comp. Zool., vol. 106, no. 9, p. 399, pl. 2, figs. 7, 12.

This species has a very scattered distribution, in most cases 625-1750 m. Frequencies are less than 1 per cent except in traverses II deeper than 620 m. and III deeper than 1000 m. where they range from 1-6 per cent.

ALVEOLOPHRAGMIUM sp.
(Plate 1, figure 22)

This species is referred to *Labrospira* sp. by Phleger and Parker (1951, p. 3). It is possible that there are two species combined here as the distribution is divided. One group is found at less than 200 m. at frequencies of less than 1 per cent, except in traverse I where they range up to 14 per cent. A second group occurs deeper than 960 m. mostly at less than 1 per cent.

AMMOSCALARIA PSEUDOSPIRALIS (Williamson)
(Plate 2, figures 3, 4)

Proteonina pseudospirale Williamson, 1858, Rec. Foram. Great Britain, p. 2, pl. 1, figs. 2, 3.

Ammobaculites prostomum Hofker, 1932, Publ. Staz. Zool. Napoli, vol. 12, fasc. 1, p. 87, figs. 14, 15.

Two variant forms are included in this species. One appears to be identical to that figured by Williamson and perhaps more accurately by Brady (1884, pl. 33, figs. 1-4). The second form, found in the vicinity of the Mississippi Delta, is smaller, longer in relation to breadth, and more finely arenaceous. The two forms are sometimes found together, but the typical form is much more widespread. A detailed study of the distribution of the small form in the Mississippi Delta area would be needed to determine whether or not this is a variant form related to a specialized environment or whether it is a different species altogether. In most respects the forms are very similar.

The species occurs in traverses I-VIII from 20-210 m. Frequencies vary from less than 1 per cent to 30 per cent in traverses I, II, IV and are less than 1 per cent elsewhere.

AMMOSCALARIA TENUIMARGO (H. B. Brady)

(Plate 2, figure 5)

Haplophragmium tenuimargo H. B. Brady, 1882, Proc. Roy. Soc. Edinburgh, vol. 11, (1880-82), p. 715; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 303, pl. 33, figs. 13-16.

The specimens are smaller than those described by Brady, being less than 1 mm. in length. The ratio of breadth to length is slightly larger.

The distribution is scattered in traverses II, V, VII-XI deeper than 950 m. Frequencies are less than 6 per cent.

AMMOBACULITES sp. A.

(Plate 2, figures 7, 8)

The specimens are very fragile, and very few are found in any one sample. It is probable that the tests are not preserved in the sediment very long after death. The species most closely resembles *A. americanus* Cushman and *A. rostratus* Heron-Allen and Earland but is not umbilicate.

A. sp. A occurs in traverses I-III, V at frequencies of less than 6 per cent except for one occurrence of 8 per cent in I at 201 m.

AMMOBACULITES sp. B.

(Plate 2, figure 6)

This species is apparently new but is not found at any one station in sufficient quantities to so describe it. It has a maximum length of 0.3 mm. and a maximum width in the coiled portion of 0.11 mm. The test is circular in cross section and has a smooth, polished, finely arenaceous wall.

It is found in all traverses except I and IV deeper than 820 m., with most occurrences deeper than 950 m. Frequencies are less than 6 per cent.

CYCLAMMINA spp.

This genus has a very scattered distribution deeper than 475 m. in most cases with frequencies of less than 1 per cent.

Family TEXTULARIIDAE

SPIROPLECTAMMINA FLORIDANA (Cushman)
(Plate 2, figure 9)

Textularia floridana Cushman, 1922, Publ. 311, Carnegie Instit. Washington, vol. 17, p. 24, pl. 1, fig. 7.

This is believed to be a valid species for the reasons given by Phleger and Parker (1951, p. 4).

It is found in traverses V-IX, XI at frequencies of less than 1 per cent, occasionally as high as 2 per cent in VI and VIII.

TEXTULARIA CANDEIANA d'Orbigny
(Plate 2, figures 16, 17)

Textularia candeiana d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 143, pl. 1, figs. 25-27.

Associated with typical *T. candeiana* are smaller specimens in which the chambers do not increase so rapidly in size as added. The two forms appear to grade into one another and are considered to belong to the same species.

There is one occurrence in traverse IV; consistent distribution is in traverses V-IX, XI to a depth of 345 m. Frequencies are less than 5 per cent.

TEXTULARIA CONICA d'Orbigny
(Plate 2, figure 13)

Textularia conica d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 143, pl. 1, figs. 19, 20.

Specimens of this species vary greatly in the amount of compression of the tests so that some in apertural view are almost completely circular while others are relatively narrow. All variations between the two extremes are observed.

The species occurs in traverses V-IX, XI down to a depth of 280 m. with frequencies of 2 per cent or less.

TEXTULARIA EARLANDI Parker
(Plate 2, figure 12)

Textularia elegans Lacroix, 1932 (not *Plecanium elegans* Hantken, 1868), Bull. Instit. Ocean. Monaco, no. 591, p. 8, text figs. 4, 6.

Textularia teuissima Earland, 1933 (not Hausler, 1881), DISCOVERY Repts., vol. 7, p. 95, pl. 3, figs. 21-30.

Textularia earlandi Parker, 1952, Bull. Mus. Comp. Zool., vol. 106, no. 10, p. 458 (footnote).

This species occurs in traverses I-V, to a depth of 1000 m. Frequencies are variable with a maximum of 79 per cent in I at station 210 and in IV at station 212. Frequencies higher than 30 per cent only occur shoaler than 80 m.

TEXTULARIA FOLIACEA OCCIDENTALIS Cushman

(Plate 2, figure 10)

Textularia foliacea Heron-Allen and Earland var. *occidentalis* Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104,, pt. 3, p. 16, pl. 2, figs. 13.

It is possible that Cushman's variety should be raised to specific rank, but this cannot be done without a study of type material. It is here given subspecific rank since the two forms are so widely separated geographically. A related form occurs rarely in this area which varies in being much less compressed. It sometimes occurs with the typical form and sometimes elsewhere. It is omitted from the population counts due to its rarity, but is found in traverses IX and XI, to a depth of 520 m.

T. foliacea occidentalis occurs in traverses V-IX, XI from 65 m. to 255 m. at frequencies of usually less than 1 per cent, occasionally slightly higher.

TEXTULARIA MAYORI Cushman

(Plate 2, figure 11)

Textularia mayori Cushman, 1922, Publ 311, Carnegie Instit. Washington, vol. 17, p. 23, pl. 2, fig. 3.

This species occurs in traverses IV-IX, XI to a depth of 150 m. with some deeper occurrences in VI and IX to a depth of 255 m. Frequencies up to 6 per cent occur shoaler than 70 m.; deeper, they are less than 1 per cent.

SIPHOTEXTULARIA CURTA (Cushman)

(Plate 2, figure 15)

Textularia flintii var. *curta* Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 14, pl. 2, figs. 2, 3.

This species occurs in traverses III, V, VI, VIII-XI from 900 m. to 2650 m. with frequencies of less than 1 per cent.

SIPHOTEXTULARIA ROLSHAUSENI Phleger and Parker
(Plate 2. figure 14)

Siphotextularia rolshauseni Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 4, pl. 1, figs. 23, 24a, b.

This is a deep-water species occurring in traverses II, V-VIII, X, XI deeper than 2100 m. In most cases frequencies are less than 1 per cent.

BIGENERINA IRREGULARIS Phleger and Parker
(Plate 3, figures 1, 2, 3)

Bigenerina irregularis Phleger and Parker, 1951, Mem. 46, Geol. Soc. America, pt. 2, p. 4, pl. 1, figs. 16-21.

This species differs from the following one in its less compressed biserial portion and smaller size. The test may be formed of calcareous fragments or sand grains depending on the materials available. Associated with this species in traverses VI-VIII is a variant form which is very slender and has a very small, more compressed biserial portion. This variant may be mistaken for a *Reophax* on superficial examination. It has a maximum length of 1.5 mm.

B. irregularis occurs in traverses IV-IX to a depth of 185 m. At less than 100 m. depth frequencies up to 5 per cent are found; deeper they are less than 1 per cent.

BIGENERINA TEXTULARIOIDEA (Goës)
(Plate 3, figures 4, 5)

Clavulina textularioidea Goës, 1894, Kongl. Svensk. Vet.-Akad. Handl., vol. 25, no. 9, p. 41, pl. 8, figs. 387-399.

This species is not reported in the northwestern Gulf of Mexico. Like the previous one the test may be formed of any material available.

It occurs in traverses V-IX, XI to a depth of 190 m. Frequencies may be as high as 6 per cent except in traverse VIII where they reach a maximum of 9 per cent.

Family VERNEUILINIDAE

GAUDRYINA cf. AEQUA Cushman
(Plate 3, figure 12)

Gaudryina aequa Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 87, pl. 18, figs. 18-21.

This species occurs in traverses V-VIII, XI to a depth of 150 m. at frequencies of less than 1 per cent.

GAUDRYINA (PSEUDOGAUDRYINA) ATLANTICA (Bailey)
(Plate 3, figure 7)

Textularia atlantica Bailey, 1851, Smithsonian Contr., vol. 2, art. 3, p. 12, pl., figs. 38-43.

This species occurs in traverses II (once), VI-IX, XI from 85 m. to 320 m. with frequencies of less than 1 per cent.

GAUDRYINA FLINTII Cushman
(Plate 3, figure 6)

Gaudryina subrotundata Flint, 1899 (not Schwager, 1866), Ann. Rept. U. S. Nat. Mus., (1897), p. 287, pl. 33, fig. 1.

Gaudryina flintii Cushman, 1911, Bull. U. S. Nat. Mus., vol. 71, pt. 2, p. 63, text fig. 102.

Specimens have a maximum length of 2 mm. and most have a shorter biserial stage than those figured by Cushman and Flint.

This species occurs in traverses VI-XI from 900 m. to 2250 m. Frequencies are not over 1 per cent.

GAUDRYINA cf. MINUTA Earland
(Plate 3, figures 15, 16)

Gaudryina minuta Earland, 1939, DISCOVERY Repts., vol. 10, p. 121, pl. 5, figs. 45, 46.

The specimens are larger and more elongate than *G. exilis* Cushman and Bronnimann and in some cases reach a greater length than that given by Earland for his species. The maximum length is 0.4 mm.

The distribution is scattered in traverses II-VIII to a depth of 1800 m. Frequencies are less than 1 per cent except in II where they reach a maximum of 8 per cent.

PSEUDOCLAVULINA MEXICANA (Cushman)
(Plate 3, figure 8)

Clavulina humilis H. B. Brady var. *mexicana* Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 83, pl. 16, figs. 1-3.

This species has a scattered distribution in all traverses but I-IV from 80 m. to 455 m., with frequencies of less than 1 per cent.

PSEUDOCLAVULINA aff. NOVANGLIAE Cushman
(Plate 3, figures 9, 10)

Clavulina nodosaria d'Orbigny var. *novangliae* Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 82, pl. 15, figs. 3-5.

This is probably a new subspecies of Cushman's species but there is insufficient material from any one locality to make a statistical analysis. The Gulf of Mexico form has a maximum length of 2 mm. and width of 0.4 mm. It appears to be a somewhat smaller form, relatively more slender, the initial triserial portion being smaller in relation to the remainder of the test. In other respects the two are similar.

This form occurs in traverses VI-IX, from 115 m. to 370 m. Frequencies are less than 1 per cent.

Family VALVULINIDAE

EGGERELLA BRADYI (Cushman)
(Plate 3, figure 17)

Verneuilina pygmaea H. B. Brady 1884 (not *Bulimina pygmaea* Egger 1857), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 385, pl. 47, figs. 4-7.

Verneuilina bradyi Cushman, 1911, Bull. U. S. Nat. Mus., vol. 71, pt. 2, p. 54, text figs. 87a, b.

As pointed out by Phleger *et al* (1953, p. 27) this species sometimes develops a biserial stage. Such specimens occur very rarely in this area.

The species occurs in all traverses but I and IV, deeper than 150 m. in a few cases but chiefly deeper than 420 m. Frequencies are less than 1 per cent shoaler than 915 m.; deeper they may be as high as 5 per cent.

TEXTULARIELLA spp.

Many of the specimens are probably referable to *T. barrettii* (Jones and Parker). Whether or not the low-spired, rapidly accelerated specimens which are found should be referred also to this species is open to question. Since the various forms have similar distributions, no attempt has been made to separate them in the population counts.

The group occurs in traverses V-IX, XI to a depth of 180 m. except in IX where they continue to 320 m. Frequencies are variable with a maximum of 3 per cent.

PLECTINA APICULARIS (Cushman)
(Plate 3, figure 18)

Gaudryina apicularis Cushman, 1911, Bull. U. S. Nat. Mus., vol. 71, pt. 2, p. 69, text figs. 110a, b.

This species occurs in all traverses but I and IV. There is a very scattered occurrence of less than 1 per cent frequency between 230 m. and 915 m.; deeper, the occurrences are more consistent and frequencies are often 1-5 per cent.

GOËSELLA MISSISSIPPIENSIS n. sp.
(Plate 3, figures 13, 14, 19)

Test of medium size, the greatest width at the apex of the triserial portion of the test which with the multiserial portion composes about five-eighths of the adult test, all stages of development being greatly accelerated, with the uniserial portion in the adult usually only consisting of a single chamber; chambers distinct, inflated; sutures slightly depressed; wall smooth, composed of rather small sand grains of varying size; aperture round or elliptical. Maximum length 0.72 mm., width 0.32 mm.

Holotype from station 28, Lat. 29°24.5′ N; Long. 88°52′ W at a depth of 106 m.

This species is smaller than *G. flintii* Cushman, has a much smoother wall composed of fine arenaceous material. The general shape of the test in the two species is very similar except that I have never seen *G. mississippiensis* with more than one uniserial chamber. Many of the specimens are juvenile, having reached only the triserial stage.

The species occurs in traverses I-IV, V (once) in most cases shoaler than 210 m. Frequencies are very high: up to 44 per cent in I, 92 per cent in II, and somewhat lower in the remaining traverses.

KARRERIELLA BRADYI (Cushman)
(Plate 3, figure 11)

Gaudryina bradyi Cushman, 1911, Bull. U. S. Nat. Mus., vol. 71, pt. 2, p. 67, text figs. 107a-c.

This species occurs chiefly in traverses VI-XI deeper than 135 m. In traverses II, III, V there are a few occurrences deeper than 900 m. All frequencies are less than 1 per cent.

LIEBUSELLA spp.

There is not sufficient material to make a study of the various species. They occur in traverse V (once), VI-IX, XI from 70 m. to 275 m. with frequencies of less than 1 per cent.

Family MILIOLIDAE

Under Miliolidae in the population counts are grouped various species which are not sufficiently common to be considered separately. Taken together they form a large group which occurs chiefly in traverses IV-XI with the majority of occurrences shoaler than 500 m. Some or all occurrences deeper than 1300 m. probably represent displaced specimens. The highest frequencies are found shoaler than 150 m., ranging in a few cases as high as 42 per cent, most frequently between 5 and 20 per cent. The frequencies decrease to less than 1 per cent at 250 m. A few occurrences deeper than 1300 m. exceed 1 per cent.

QUINQUELOCULINA BICOSTATA d'Orbigny

(Plate 4, figures 1, 2)

Quinqueloculina bicostata d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 195, pl. 12, figs. 8-10.

Gulf of Mexico specimens are larger than d'Orbigny's, reaching a maximum length of 0.9 mm.

The species occurs in traverses IV-VIII to a depth of 100 m. except in VIII where it goes to 145 m. Most frequencies are less than 1 per cent; a few shoaler than 50 m. reach a maximum of 3 per cent.

QUINQUELOCULINA COMPTA Cushman

(Plate 3, figures 20, 21)

Quinqueloculina compta Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 87, pl. 19, fig. 2.

The distribution is in traverses IV-VIII, XI (once), to a depth of 155 m. Frequencies up to 3 per cent occur shoaler than 50 m.; deeper, they are less than 1 per cent.

QUINQUELOCULINA HORRIDA Cushman
(Plate 4, figures 3, 4)

Quinqueloculina horrida Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 88, pl. 19, fig. 1.

The species occurs in traverses IV-IX to a depth of 370 m. With a few exceptions all frequencies are less than 1 per cent, never greater than 3 per cent.

QUINQUELOCULINA LAMARCKIANA d'Orbigny
(Plate 4, figures 5, 6)

Quinqueloculina lamarckiana d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 189, pl. 11, figs. 14, 15.

This species, as I have defined it in this area, may represent a "species group" rather than a discrete species. There is great variation in the acuteness of the chamber angles and the extent to which they project. There is also variation in the length of the apertural neck.

The distribution is in traverses IV-XI to a depth of 275 m.; scattered deeper than 180 m. Frequencies are 1-5 per cent at the shoaler ends of the traverses extending to various depths but never deeper than 150 m. There are a few specimens, probably displaced, found deeper than 1500 m. in traverses II and X.

QUINQUELOCULINA cf. POLYGONA d'Orbigny
(Plate 4, figures 7, 8)

Quinqueloculina polygona d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 198, pl. 12, figs. 21-23.

This species is very similar to d'Orbigny's figured specimen but is relatively broader, has a more elongate aperture and a shorter neck.

Specimens occur in traverses IV-IX, XI, consistently to a depth of 100 m.; scattered to 185 m. All frequencies are less than 1 per cent.

QUINQUELOCULINA SABULOSA Cushman
(Plate 4, figures 9, 10)

Quinqueloculina sabulosa Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 87, pl. 18, fig. 22.

This species occurs in traverses IV-VIII to a depth of 100 m. All frequencies are less than 1 per cent.

QUINQUELOCULINA VENUSTA Karrer
(Plate 4, figures 13, 14)

Quinqueloculina venusta Karrer, 1868, Sitz. K. Akad. Wiss. Wien, vol. 58, Abt. 1, p. 147, pl. 2, fig. 6.

This species occurs in traverse VI (once), VIII (once), IX-XI, deeper than 1700 m. Frequencies are less than 1 per cent except for one occurrence of 2 per cent at 3164 m. in VIII.

QUINQUELOCULINA sp.
(Plate 4, figures 11, 12)

This species is similar to the form referred by Phleger *et al* (1953, p. 28) to *Q.* cf. *weaveri* Rau, except that it has a small, simple tooth. The species is not sufficiently common to describe adequately. The maximum length is 0.6 mm.

It occurs in traverses II, III, V-XI, but chiefly in VI-XI deeper than 915 m., except in VII where it occurs deeper than 585 m. Frequencies are less than 1 per cent except occasionally in IX-XI where the maximum is 3 per cent.

SPIROLOCULINA cf. GRATA Terquem
(Plate 4, figure 15)

Spiroloculina grata Terquem, 1878, Mém. Soc. Géol. France, ser. 3, vol. 1, p. 55, pl. 5 (10), figs. 14, 15.

This species is referred by Phleger and Parker (1951, p. 8) to *S. antillarum* d'Orbigny. I sent specimens to Miss Ruth Todd for study and she agrees that they closely resemble *S. grata.* The test of *S. antillarum* has a polished surface, *S. grata* a dull, slightly roughened one.

S. cf. *grata* occurs in traverses IV-VIII to a depth of 145 m. except in VIII where it extends to 585 m. Frequencies are mostly less than 1 per cent; 1 per cent occasionally.

SPIROLOCULINA SOLDANII Fornasini
(Plate 4, figure 16)

Frumentaria sextae speciei Soldani, 1780, Saggio Orittografico, p. 111, pl. 9, figs. 52t, T, V.

Spiroloculina soldanii Fornasini, 1886, Boll. Soc. Geol. Ital., vol. 5, p. 25.

There is some question whether or not this may be a gradational form of *S. depressa* d'Orbigny. Miss Ruth Todd reports (personal communication) that the two species grade into one another. A careful study of type and topotype material should be made to determine this. I am referring the Gulf of Mexico species to *S. soldanii* since it resembles this form more closely.

It occurs in traverses IV-IX, XI to a depth of 320 m. Most frequencies are less than 1 per cent.

SIGMOILINA DISTORTA Phleger and Parker
(Plate 4, figures 17, 21)

Sigmoilina distorta Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 8, pl. 4, figs. 3-5.

This species occurs chiefly in traverses IV-VIII, with rare occurrences in IX-XI. Most occurrences are shoaler than 500 m. but there are a few deeper ones, possibly displaced, in X and XI. Frequencies are variable with a maximum of 3 per cent.

SIGMOILINA SCHLUMBERGERI A. Silvestri
(Plate 4, figure 18)

Sigmoilina schlumbergeri A. Silvestri, 1904, Mem. Pont. Accad. Nuovi Lincei, vol. 22, p. 267.

This species is widely distributed in all traverses but I and IV, deeper than 175 m. The most consistent occurrence is deeper than 585 m. All occurrences shoaler than 915 m. have a frequency of less than 1 per cent; slightly higher ones occur occasionally in deeper water.

SIGMOILINA TENUIS (Czjzek)
(Plate 4, figure 19)

Quinqueloculina tenuis Czjzek, 1848, Haidinger's Nat. Abhandl. vol. 2, p. 149, pl. 13, figs. 31-34.

This species occurs in traverses III (once), V (twice), VI-XI, deeper than 140 m. All frequencies are less than 1 per cent except at the inner ends of IX and XI where frequencies of 1 per cent occur.

SIGMOILINA sp.
(Plate 5, figure 1, Text figure 2)

This species may be referable to "*Spiroloculina arenaria*" H. B. Brady. Sectioning shows that the Gulf of Mexico form is a *Sigmoilina* and since it would be preferable to section Brady's specimens before transferring his species to *Sigmoilina* I have not given the Gulf of Mexico species a name at this time.

The species occurs in traverses V (once), VI-IX, XI to a depth of 255 m. Frequencies are less than 1 per cent except in VII where they are 1 and 3 per cent at 86 m. and 146 m. respectively.

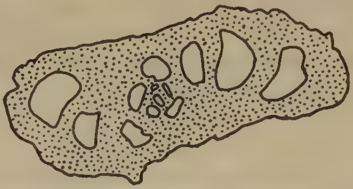

Fig. 2. *Sigmoilina* sp. Transverse section. X 55. Sta. 59.

NUMMOLOCULINA IRREGULARIS (d'Orbigny)

(Plate 4, figure 20)

Biloculina irregularis d'Orbigny, 1839, Voy. Amer. Mérid., vol. 5, pt. 5, "Foraminifères," p. 67, pl. 8, figs. 20, 21.

The distribution of this species is very scattered. It occurs in traverse IX from 320 m. to 425 m., in traverses II (once), III (once), X, XI deeper than 914 m. Frequencies are less than 1 per cent except in X (once) and XI where they reach a maximum of 5 per cent.

TRILOCULINA cf. BREVIDENTATA Cushman

(Plate 5, figures 2, 3)

Triloculina brevidentata Cushman, 1944, Spec. Publ. 12, Cushman Lab. Foram. Res., p. 16, pl. 2, figs. 25a, b.

Gulf of Mexico specimens are relatively broader than those of Cushman's species and the chambers are slightly more inflated.

This species occurs in traverses IV-IX, XI to a depth of 255 m. Frequencies are less than 1 per cent except in V where there is a maximum of 2 per cent at the inner end and VII with a maximum of 1 per cent at the inner end.

TRILOCULINA TRICARINATA d'Orbigny

(Plate 4, figure 22)

Triloculina tricarinata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 299, no. 7; Modèles, no. 94.

The distribution is scattered in all traverses but I and IV. The most consistent occurrence is deeper than 1000 m. but the species is found deeper than 55 m. Frequencies are usually less than 1 per cent, never more than 1 per cent.

PYRGO MURRHINA (Schwager)
(Plate 5, figure 7)

Biloculina murrhina Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 203, pl. 4, figs. 15 a-c.

There is a good deal of variation in the sinus at the base of the test. It is sometimes curved with two sharp points at either end and may be straight with no projecting points.

This species is widely distributed in all traverses except I and IV but most occurrences are in VI-XI. It is found at all depths but is more abundant deeper than 900 m. where frequencies as high as 4 per cent occur in IX-XI. Elsewhere frequencies are less than 1 per cent.

PYRGO cf. NASUTUS Cushman
(Plate 5, figure 4)

Pyrgo nasutus Cushman, 1935, Smithsonian Misc. Coll., vol. 91, no. 21, p. 7, pl. 3, figs. 1-4.

Gulf of Mexico specimens have a less serrate periphery than the form described by Cushman.

The species occurs in traverses III-IX, XI to a depth of 530 m. Frequencies are usually less than 1 per cent; occasionally slightly higher.

Family OPHTHALMIDIIDAE

NODOBACULARIELLA CASSIS (d'Orbigny)
(Plate 5, figure 8)

Vertebralina cassis d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 51, pl. 7, figs. 14, 15.

N. atlantica Cushman and Hanzawa may be included in the population counts under this species. The specimens are often much worn and specific identification difficult.

N. cassis occurs in traverses IV-VIII, IX (once), XI. Most occurrences are shoaler than 150 m., a few extending to 240 m. At less than 100 m. frequencies up to 5 per cent occur, with one occurrence in VIII of 11 per cent. Deeper than 100 m. frequencies are less than 1 per cent.

WIESNERELLA AURICULATA (Egger)
(Plate 5, figure 13)

Planispirina auriculata Egger, 1893, Abhandl. k. bay. Akad. Wiss. München, vol. 18, pt. 2, p. 245, pl. 3, figs. 13-15.

This species occurs chiefly in traverses V-VIII, with single occurrences in I and III, and two in IV. All but two occurrences are shoaler than 185 m. Frequencies are less than 1 per cent.

Family TROCHAMMINIDAE

TROCHAMMINA ADVENA Cushman
(Plate 5, figures 5, 6)

Trochammina advena Cushman, 1922, Publ. 311, Carnegie Instit. Washington, p. 20, pl. 1, figs. 2-4.

This species occurs at frequencies of 1-5 per cent in traverse I from 128 m. to 430 m. Other occurrences are scattered in traverses II, III, V, VI at various depths to 1100 m., at frequencies of less than 1 per cent (except for one occurrence of 4 per cent in II at 314 m.).

TROCHAMMINA GLOBULOSA Cushman
(Plate 5, figures 11, 12)

Trochammina globulosa Cushman, 1920, Bull. U. S. Nat. Mus., vol. 104, pt. 2, p. 77, pl. 16, figs. 3, 4.

There is some variation in the texture of the test walls, some being smoother and more fine grained than others. The specimens were not as big as Cushman's, having a maximum diameter of 0.62 mm.

The species occurs in all traverses but I and IV deeper than 1000 m., except in II where it occurs deeper than 915 m., with frequencies up to 6 per cent.

TROCHAMMINA cf. JAPONICA Ishiwada
(Plate 5, figures 9, 10)

Trochammina japonica Ishiwada, 1950, Japan Geol. Surv. Bull., Kawasaki, Japan, vol. 1, no. 4, p. 190, pl., figs. 2a-c.

Northeastern Gulf of Mexico specimens are the same as *Trochammina* sp. Phleger and Parker (1951, p. 9).

The occurrence is most consistent in traverses I-III from 200 m. to 1750 m. at frequencies from 1 to 13 per cent. In traverses V-VII, X, XI the species has a scattered distribution at all depths deeper than 130 m. with frequencies less than 1 per cent.

TROCHAMMINA QUADRILOBA Höglund
(Plate 5, figures 14, 15)

Trochammina pusilla Höglund, 1947, (not *Serpula pusilla* Geinitz, 1848), Zool. Bidrag Uppsala, vol. 26, p. 201, pl. 17, figs. 4a-c, text figs. 183, 184.

Trochammina quadriloba Höglund, 1948, Contr. Cushman Lab. Foram. Res., vol. 24, pt. 2, p. 46.

This species has a very scattered distribution at various depths except in traverses I-III where it occurs between 70 m. and 430 m. Frequencies are as high as 22 per cent in I and 17 per cent, shoaler than 210 m., in II. Elsewhere frequencies are less than 1 per cent except for one occurrence of 6 per cent in II at 914 m.

TROCHAMMINA SQUAMATA Jones and Parker and related spp.

Trochammina squamata Jones and Parker, 1860, Quart. Journ. Geol. Soc. London, vol. 16, p. 304; Parker and Jones, 1865, Philos. Trans. Roy. Soc. London, vol. 155, p. 407, pl. 15, figs. 30, 30a-c.

Representatives of this group occur in all traverses but II and IX usually shallower than 100 m. Frequencies are mostly less than 1 per cent although they are occasionally as high as 5 per cent.

TROCHAMMINA cf. TASMANICA Parr
(Plate 5, figures 16, 17)

Trochammina tasmanica Parr, 1950, B. A. N. Z. Antarctic Res. Exped. 1929-31, ser. B, vol. 5, pt. 6, p. 279, pl. 5, fig. 18.

Gulf of Mexico forms are similar to Parr's but are smaller, with a maximum diameter of 0.26 mm., and appear to have a slightly higher spire.

This species has a very scattered occurrence throughout the area with frequencies in traverses I-III, where it occurs most consistently, up to 5 per cent (once 18 per cent). Other frequencies are less than 1 per cent.

NOURIA POLYMORPHINOIDES Heron-Allen and Earland
(Plate 5, figure 19)

Nouria polymorphinoides Heron-Allen and Earland, 1914, Trans. Zool. Soc. London, vol. 20, pt. 12, p. 376, pl. 37, figs. 1-15.

Proteonina comprima Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 2, pl. 1, figs. 1-3.

The distribution is in traverses IV, V, VII, VIII to a depth of 75 m. Frequencies are less than 1 per cent except for one occurrence of 9 per cent in IV at 40 m.

NOURIA sp.

(Plate 5, figure 20)

This species is smaller than *N. polymorphinoides* with a more regular oval shape and more finely arenaceous wall. The wall is constructed of sand grains of irregular size, some being much larger than others, and is very thin and fragile. It may be new.

It occurs in traverses I-IV to a depth of 130 m. Frequencies are high with maxima of 59 per cent in I, 81 per cent in II, 11 per cent in III and 22 per cent in IV.

Family LAGENIDAE

ROBULUS spp.

All species of this genus are combined in the population counts. They occur in all traverses, except I, at all depths. Occurrences are scattered in traverses II-IV. Frequencies of 1-5 per cent occur to a depth of 450 m. in VI-IX, XI; elsewhere they are less than 1 per cent.

LENTICULINA PEREGRINA (Schwager)

(Plate 5, figure 18)

Cristellaria peregrina Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 245, pl. 7, fig. 89.

This species has a wide distribution in all traverses except I and IV. Most occurrences are deeper than 145 m. Frequencies are less than 1 per cent.

MARGINULINA MARGINULINOIDES (Goës)

(Plate 5, figure 21)

Cristellaria aculeata var. *marginulinoides* Goës, 1896, Bull. Mus. Comp. Zool., vol. 29, p. 56, pl. 5, figs. 15, 16.

No keeled specimens are found but in other respects this form closely resembles Goës' species. Other species of *Marginulina* are found in the area but occur only rarely, being confined to a depth of less than 500 m.

The distribution is scattered with single occurrences in traverses II, V, VIII and more consistent occurrences in VI and VII. The depth range is 50 m. to 450 m. All frequencies are less than 1 per cent.

DENTALINA spp., NODOSARIA spp.

These genera have a scattered distribution at all depths, usually deeper than 100 m. Frequencies are low.

NODOSARIA HISPIDA d'Orbigny

(Plate 6, figure 1)

Nodosaria hispida d'Orbigny, 1846, Foram. Foss. bass. tert. Vienne, p. 35, pl. 1, figs. 24, 25.

Specimens which may be referred to var. *sublineata* H. B. Brady are included here though most of them are hirsute in character.

Single occurrences are found in traverses V, IX, XI; more consistent ones in VI-VIII. They occur deeper than 145 m. and, with one exception, no deeper than 715 m. Frequencies are less than 1 per cent.

PSEUDOGLANDULINA COMATULA (Cushman)

(Plate 5, figure 22)

Nodosaria comatula Cushman, 1923, Bull. U. S. Nat. Mus., vol. 104, pt. 4, p. 83, pl. 14, fig. 5.

There is a scattered distribution in traverses VI-XI, mostly between 135 and 255 m. Frequencies are less than 1 per cent.

LAGENA spp. and related forms

The species included in this group usually have a scattered or rare occurrence but the group taken as a whole is an important part of the fauna, occurring in all traverses but I at all depths. Frequenices are usually less than 1 per cent to a depth of 140 m., 1-5 per cent elsewhere except in traverses II (once), X, and XI where they may be as high as 10 per cent.

Family POLYMORPHINIDAE

GUTTULINA AUSTRALIS (d'Orbigny)
(Plate 6, figure 2)

Globulina australis d'Orbigny, 1839, Voy. Amer. Mérid., vol. 5, pt. 5, "Foraminifères," p. 60, pl. 1, figs. 1-4.

This species occurs in traverses IV-VIII to a depth of 85 m. Frequencies are usually less than 1 per cent but reach a maximum of 2 per cent at the inner end of IV.

GLOBULINA CARIBAEA d'Orbigny
(Plate 5, figure 23)

Globulina caribaea d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 135, pl. 2, figs. 7, 8.

Occurrences are in traverses IV-VIII to a depth of 58 m. Frequencies are less than 1 per cent.

Family NONIONIDAE

NONION FORMOSUM (Seguenza)
(Plate 6, figure 3)

Nonionina formosa Seguenza, 1880, Atti R. Accad. Lincei, ser. 3, vol. 6, p. 63, pl. 7, figs. 6, 6a.

Nonion barleeanum (Williamson) var. *inflatum* van Voorthuysen, 1950 (not *Nonionina inflata* Alth, 1850), Meded. Geol. Sticht., n. s., no. 4, p. 41, text fig. 7, pl. 3, figs. 6a, b.

Anomalinoides barleeanum (Williamson) var. *zaandamae* (van Voorthuysen) van Voorthuysen, 1952, Journ. Pal., vol. 26, no. 4, p. 681.

Comparison with specimens sent by van Voorthuysen and of these with topotype material of *N. formosum* at the U. S. National Museum by A. R. Loeblich appears to confirm this identification. Similar specimens were so referred by Phleger *et al* (1953, p. 30).

This species occurs in traverses V-IX, XI from 60 m. to 1750 m. Most frequencies are less than 1 per cent.

NONION POMPILIOIDES (Fichtel and Moll)
(Plate 6, figure 4)

Nautilus pompilioides Fichtel and Moll, 1798, Test. Micr., p. 31, pl. 2, figs. a-c.

There are single occurrences in traverses III, VI, VIII and X and there is a more consistent distribution in traverses II, VII, IX, XI. All occurrences are deeper than 2200 m. Frequencies are usually 1-4 per cent except at the outer end of XI where they are as high as 8 per cent.

ASTRONONION TUMIDUM Cushman and Edwards

(Plate 6, figure 5)

Nonionina stelligera H. B. Brady (pt.), 1884 (not d'Orbigny 1839), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 728, pl. 109, fig. 5 (not figs. 3, 4).

Astrononion tumidum Cushman and Edwards, 1937, Contr. Cushman Lab. Foram. Res., vol. 13, pt. 1, p. 33, pl. 3, fig. 17.

The only reported occurrence of this species is that of Brady's figured specimen from CHALLENGER station 344, in 240 fms. off Ascension Island, south Atlantic.

There are single occurrences in traverses V, VI, IX, and XI, consistent ones in VII, VIII, X. The depth range is 320 m. to 1400 m., with one occurrence at 2550 m. All frequencies are less than 1 per cent.

NONIONELLA ATLANTICA Cushman

(Plate 6, figures 6, 7)

Nonionella atlantica Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 90, pl. 20, figs. 4, 5.

Combined in the population counts with this species are specimens of a more compressed form (Pl. 6, figs. 8, 9) and a small form which resembles *N. sloanii* (d'Orbigny).

N. atlantica occurs in traverses II-VIII, XI (once). The most consistent occurrence is shoaler than 500 m. with frequencies up to 10 per cent shoaler than 140 m., less than 1 per cent deeper than 140 m. A few single occurrences are at great depths and probably represent displaced specimens.

NONIONELLA OPIMA Cushman

(Plate 6, figures 10, 11, 12)

Nonionella opima Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 90, pl. 20, figs. 1-3.

This species occurs in traverses I-VII, XI. Consistent occurrences are found shoaler than 400 m. and scattered ones deeper. Frequencies up to 20 per cent may occur shoaler than 100 m., up to 5 per cent deeper. There is one occurrence of 31 per cent in III at 53 m.

ELPHIDIUM ADVENUM (Cushman)
(Plate 6, figure 14)

Polystomella advena Cushman, 1922, Publ. 311, Carnegie Instit. Washington, p. 56, pl. 9, figs. 11, 12.

The specimens in this area have a larger umbo than those described by Cushman. In other respects they appear similar.

All occurrences are shoaler than 115 m. in traverses IV-VIII. Frequencies are in most cases less than 1 per cent.

ELPHIDIUM DISCOIDALE (d'Orbigny)
(Plate 6, figure 15)

Polystomella discoidalis d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 56, pl. 6, figs. 23, 24.

This species occurs in traverses IV-VIII shoaler than 185 m. Frequencies are up to 5 per cent to a depth of 100 m., less than 1 per cent deeper.

ELPHIDIUM GUNTERI Cole
(Plate 6, figure 16)

Elphidium gunteri Cole, 1931, Florida State Geol. Surv. Bull. 6, p. 34, pl. 4, figs. 9, 10.

Elphidium gunteri Cole var. *galvestonensis* Kornfeld, 1951, (part), Contr. Dept. Geol. Stanford Univ., vol. 1, no. 3, p. 87, pl. 15, figs. 2a, b, 3a, b (not figs. 1a, b).

?*Elphidium littorale* Le Calvez and Le Calvez, 1951, Vie et Milieu, vol. 2, no. 2, p. 251, text figs. 5a, b.

E. littorale is placed in the synonymy questionably because the types have not been seen. It appears from the description and figures, however, to be synonymous. The only apparent difference is that it is described as having 10-12 chambers in the last-formed whorl whereas Cole's species may have as many as 14. As stated by Parker *et al* (1953, p. 8) part of Kornfeld's form *E. gunteri* var. *galvestonensis* is referable to *E. gunteri* as shown by a study of his types.

E. gunteri occurs in traverses III (once), IV-VIII to a depth of 80 m. except in VIII where it occurs to a depth of 185 m. Frequencies up to 5 per cent occur shoaler than 55 m., less than 1 per cent deeper. There are two occurrences of 9 per cent at the inner ends of IV and V.

ELPHIDIUM POEYANUM (d'Orbigny)
(Plate 6, figure 17)

Polystomella poeyana d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 55, pl. 6, figs. 25, 26.

The species occurs in traverses IV-VIII shoaler than 145 m. Frequencies up to 2 per cent occur at the inner end of various traverses; elsewhere they are less than 1 per cent.

ELPHIDIUM spp.

This group includes various species which have very low frequency distributions when considered separately. It occurs mostly in traverses III-VIII with some occurrences in I, II, IX, XI. Frequencies up to 5 per cent occur to a depth of 150 m., less than 1 per cent deeper. Occurrences are consistent to 185 m. and extend deeper in V and XI.

Family PENEROPLIDAE

This family has been considered as a group owing to the impossibility of identifying a relatively high proportion of the specimens. Many are badly weathered and there is usually a profusion of juvenile forms present.

The distribution is shoaler than 145 m. in traverses IV-VIII, with a single occurrence in XI. There is one occurrence in II at 375 m. Frequencies up to 16 per cent shoaler than 60 m., up to 5 per cent shoaler than 90 m. and less than 1 per cent elsewhere.

Family BULIMINIDAE

BULIMINELLA cf. BASSENDORFENSIS Cushman and Parker
(Plate 6, figure 13)

Buliminella bassendorfensis Cushman and Parker, 1937, Contr. Cushman Lab. Foram. Res., vol. 13, pt. 1, p. 40, pl. 4, figs. 13a, b.

This species occurs in traverses I-VI to a depth of 80 m. except in III where it extends to 370 m. at a frequency of less than 1 per cent. There are two occurrences deeper than 1700 m. Frequencies are variable but reach a maximum of 35 per cent at 77 m. in III.

ROBERTINA BRADYI Cushman and Parker
(Plate 6, figure 18)

Robertina bradyi Cushman and Parker, 1936, Contr. Cushman Lab. Foram. Res., vol. 12, p. 99, pl. 16, figs. 9a, b.

This species has a scattered occurrence in traverses VI-VIII and a more consistent one in IX-XI. The depth range is 105 m. to 2600 m. Frequencies are less than 1 per cent except in X and XI where they reach a maximum of 2 per cent deeper than 1300 m.

BULIMINA ACULEATA d'Orbigny
(Plate 6, figure 19)

Bulimina aculeata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 7.

This species is widely distributed in all traverses except I and IV deeper than 220 m., except for a shallow occurrence in III. Between 370 m. and 1850 m. frequencies up to 16 per cent occur; elsewhere they are usually less than 1 per cent.

BULIMINA ALAZANENSIS Cushman
(Plate 6, figure 21)

Bulimina alazanensis Cushman, 1927, Journ. Pal., vol. 1, p. 161, pl. 25, fig. 4.

This is a widely distributed species in all traverses but I and IV, deeper than 220 m. Frequencies are usually 1-5 per cent but may be as high as 15 per cent.

BULIMINA MARGINATA d'Orbigny
(Plate 6, figure 20)

Bulimina marginata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 269, no. 4, pl. 12, figs. 10-12.

As in the northwestern Gulf of Mexico, specimens are smaller than typical, more spinose, and have more undercut chambers.

This species occurs in traverses II-VII to a depth of 530 m. It does not occur shoaler than 75 m. except in IV. Frequencies are very variable, reaching a maximum of 33 per cent in II at 168 m. Deeper than 320 m. frequencies are less than 1 per cent.

BULIMINA SPICATA Phleger and Parker
(Plate 6, figures 22, 23)

Bulimina spicata Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 16, pl. 7, figs. 25a-c, 30, 31.

This is a widely distributed species in all but traverses I and IV deeper than 70 m. Frequencies vary up to a maximum of 5 per cent.

BULIMINA STRIATA MEXICANA Cushman
(Plate 6, figure 24)

Bulimina striata d'Orbigny var. *mexicana* Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 95, pl. 21, fig. 2.

This species occurs in all traverses but I and IV deeper than 170 m. Frequencies seldom exceed 5 per cent.

GLOBOBULIMINA AFFINIS (d'Orbigny) and variant
(Plate 6, figure 25; Plate 7, figures 1, 2)

Bulimina affinis d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 105, pl. 2, figs. 25, 26.

Occurring with, or independently of, the typical form are specimens which are relatively much more narrow. These forms appear to have a somewhat deeper range, although there are exceptions. It is often difficult to separate the two forms, and for this reason they have been combined in the population counts.

The distribution is rather scattered in all traverses except I and IV, deeper than 165 m. Frequencies up to 5 per cent occur.

GLOBOBULIMINA MISSISSIPPIENSIS n. sp.
(Plate 7, figures 3, 4, 10)

Test of medium size, ovate, with the greatest width usually below or near the middle, sometimes almost as long as broad; initial end rounded in the megalospheric form, slightly pointed in microspheric; chambers slightly inflated, the last-formed whorl making up 1/8 to 1/7th of the test; sutures very slightly depressed; wall thin, translucent, finely perforate; aperture with a thickened border, the tongue extending from the test, curved, with a regular, non-toothed border. Maximum length 0.51 mm.; width 0.36 mm.

Holotype from station 29, Lat. 29°04.5′ N; Long. 88°52′ W at 155 m.

This species differs from *G. ovula* (d'Orbigny) in the non-depressed suture and non-inflated area of the last-formed chamber leading down from the aperture; the remaining chambers also are less inflated so that the outline of *G. mississippiensis* is much more regular. The species from the Caribbean discussed by Höglund (1947, p. 244) as *G.* sp. A is much larger, has fewer chambers, a deeply depressed portion of the suture near the aperture, and the last-formed whorl makes up a greater portion of the test.

There are single occurrences in traverses I and II and consistent ones in III from 105-205 m. Frequencies in III are 2-3 per cent.

VIRGULINA ADVENA Cushman
(Plate 7, figure 5)

Virgulina (?) advena Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 120, pl. 25, figs. 1-3.

As pointed out by Phleger *et al* (1953, p. 34) this appears to be a true *Virgulina.*

It has a scattered occurrence in all traverses but I and IV, deeper than 1250 m. Most frequencies are less than 1 per cent but they reach a maximum of 2 per cent at 2697m. in VI.

VIRGULINA COMPLANATA Egger
(Plate 7, figure 6)

Virgulina schreibersiana Czjzek var. *complanata* Egger, 1893, Abhandl. k. bay. Akad. Wiss. München, vol. 18, pt. 2, p. 292, pl. 8, figs. 91, 92.

This is a widely distributed species in all traverses but I and at all depths. Frequencies are less than 1 per cent.

VIRGULINA MEXICANA Cushman
(Plate 7, figures 7, 8)

Virgulina mexicana Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 120, pl. 23, fig. 8.

This species is widely distributed but does not occur consistently. It occurs in all traverses but I and IV deeper than 110 m. Frequencies are less than 1 per cent.

Virgulina pontoni Cushman
(Plate 7, figure 9)

Virgulina pontoni Cushman, 1932, Contr. Cushman Lab. Foram. Res., vol. 8, pt. 1, p. 17, pl. 3, fig. 7.

This species has a scattered occurrence in all traverses but IX-X. Most occurrences are shoaler than 205 m. but some go to 530 m., with two deep occurrences in XI. Frequencies may be as high as 4 per cent, shoaler than 105 m.; deeper they are less than 1 per cent in most cases.

Virgulina punctata d'Orbigny
(Plate 7, figure 11)

Virgulina punctata d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, ''Foraminifères,'' p. 139, pl. 1, figs. 35, 36.

This species occurs in traverses III-VIII, X, XI. The most concentrated occurrence is shoaler than 150 m. but in V, X, XI specimens occur to a depth of 2550 m. Shoaler than 130 m. frequencies may be as high as 5 per cent; deeper they are less than 1 per cent.

Virgulina tessellata Phleger and Parker
(Plate 7, figure 12)

Virgulina tessellata Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 19, pl. 9, figs. 15a, b, 16a, b.

This species occurs in traverses II, III, V-VIII, XI (once) from 375-2200 m. Shoaler than 1000 m. frequencies are usually less than 1 per cent but may be as high as 2 per cent; deeper than 1000 m. they reach a maximum of 15 per cent at 1262 m. in III.

Bolivina albatrossi Cushman
(Plate 7, figure 13)

Bolivina albatrossi Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 31, pl. 6, fig. 4.

This species has a wide distribution, most commonly from 145 m. to 1900 m. but with scattered occurrences elsewhere. Frequencies may be as high as 10 per cent between 180 m. and 1300 m.

BOLIVINA BARBATA Phleger and Parker
(Plate 7, figure 14)

Bolivina barbata Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 13, pl. 6, figs. 12a, b, 13.

This species has a scattered occurrence in traverses I-III, V-VII. Most occurrences are shoaler than 205 m. but extend, mostly in V, to 530 m. Frequencies are variable reaching a maximum of 26 per cent in III at 155 m. In most cases deeper than 205 m. they are less than 1 per cent.

BOLIVINA FRAGILIS Phleger and Parker
(Plate 7, figure 15)

Bolivina fragilis Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 13, pl. 6, figs. 14, 23, 24a, b.

This species occurs in traverses V-IX, XI shoaler than 255 m. (3 exceptions). Frequencies from 1-5 per cent occur from 100-255 m. with one occurrence of 7 per cent in V at 146 m.

BOLIVINA GOËSII Cushman
(Plate 7, figure 16)

Bolivina goësii Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 34, pl. 6, fig. 5.

This species occurs in traverses VI-XI from 135 m. to 320 m. with a few scattered low-frequency occurrences deeper. Frequencies vary up to a maximum of 7 per cent in IX at 256 m.

BOLIVINA LANCEOLATA n. sp.
(Plate 7, figures 17, 18, 19, 20)

Test regularly tapered, initial end sometimes with a very short spine, compressed, periphery acute, sometimes with a very narrow keel, especially on the last-formed chambers; chambers uninflated, narrow, increasing gradually in height as added; sutures very slightly limbate, straight, at an angle of forty-five degrees with the horizontal; wall with medium-sized perforations except on clear areas on the inner and upper portion of the earlier chambers, sometimes with a few fine costae extending two-thirds of the way up the test; aperture narrow, keeled. Maximum length 0.6 mm.; width 0.14 mm.

Holotype from station 180, Lat. 29°04′ N, Long. 85°49′ W, at a depth of 183 m.

This species differs from *B. acerosa* Cushman in having a larger test, a higher ratio of breadth to length, and in having clear areas on the inner portions of the chambers. The initial portion of the test is less closely costate, but the costae when present extend farther up the test. It differs from *B. punctata* d'Orbigny in having costae, in being keeled on the later portion of the test rather than the earlier portion, and in the less curved sutures.

This species is widely distributed in traverses V-XI, deeper than 45 m. Frequencies are usually low but may be as high as 4 per cent.

BOLIVINA LOWMANI Phleger and Parker
(Plate 7, figure 21)

Bolivina lowmani Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 13, pl. 6, figs. 20a, b, 21.

This is a very common, widely distributed species in all traverses but I, at all depths. Frequencies are usually 1-5 per cent but reach a maximum of 8 per cent in VIII at 1730 m.

BOLIVINA MINIMA Phleger and Parker
(Plate 7, figures 22, 23)

Bolivina minima Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 14, pl. 6, figs. 22a, b, 25; pl. 7, figs. 1, 2.

This species is a very common one in traverses V-XI deeper than 110 m. with a single occurrence in IV at 55 m. Frequencies to a depth of 530 m. vary from 1-14 per cent; they do not exceed 5 per cent between 530 m. and 915 m. Deeper than this they are less than 1 per cent.

BOLIVINA ORDINARIA Phleger and Parker
(Plate 7, figure 24)

Bolivina simplex Phleger and Parker, 1951 (not *B. interjuncta* Cushman var. *simplex* Cushman and Renz, 1941), Mem. Geol. Soc. America, vol. 46, pt. 2, p. 14, pl. 7, figs. 4-6.

Bolivina ordinaria Phleger and Parker, 1952, Contr. Cushman Found. Foram. Res., vol. 3, pt. 1, p. 14.

This species is widely distributed in all traverses but I and IV deeper than 115 m. (one exception). The most consistent distribution is not deeper than 1800 m. but there are scattered occurrences deeper. Frequences are variable reaching a maximum of 19 per cent in III at 205 m.

BOLIVINA PAULA Cushman and Cahill
(Plate 7, figure 26)

Bolivina paula Cushman and Cahill, 1932, in Cushman and Ponton, Bull. Florida State Geol. Surv. vol. 9, p. 84, pl. 12, figs. 6a, b.

This species is reported from the Recent in the North Atlantic (Phleger, *et al*, 1953, p. 35) in displaced faunas from shallower water. Other reports are from the Miocene of the eastern United States.

It has a scattered occurrence at all depths in traverses II, V-XI. Frequencies are less than 1 per cent.

BOLIVINA PULCHELLA PRIMITIVA Cushman
(Plate 7, figure 36)

Bolivina pulchella (d'Orbigny) var. *primitiva* Cushman, 1930, Bull. Florida State Geol. Surv., vol. 4, p. 47, pl. 8, figs. 12a, b.

No specimens of typical *B. pulchella* occur in this area.

Occurrences are in traverses II, IV-XI at all depths. Frequencies are less than 1 per cent in most cases.

BOLIVINA PUSILLA Schwager
(Plate 7, figure 31)

Bolivina pusilla Schwager, 1866, Novara-Exped. Geol. Theil., vol. 2, p. 254, pl. 7, fig. 101.

Specimens are the same size as those described by Schwager (0.35 mm. in length) but smaller than those observed in the North Atlantic by Phleger *et al* (1953, p. 36) which have a maximum length of 0.54 mm.

There are three shallow occurrences at less than 250 m. but the species usually occurs deeper than 1300 m. in traverses II, III, V, VI, VII-XI. Frequencies are less than 1 per cent except in V where they reach a maximum of 2 per cent.

BOLIVINA STRIATULA SPINATA Cushman
(Plate 7, figure 29)

Bolivina striatula Cushman var. *spinata* Cushman, 1936, Spec. Publ. no. 6, Cushman Lab. Foram. Res., p. 59, pl. 8, figs. 9a, b.

The types of *B. striatula* have not been studied but a comparison with specimens of that species from shallow water of the San Antonio Bay region off Texas show that the spinate form should perhaps be given specific rank. It is less compressed, more striate and has an initial spine. Included here with typical specimens are some that are narrower and less strongly striated. Typical specimens seem to grade into this variant especially in the region to the east of traverse V.

With two exceptions the distribution is shoaler than 240 m. in traverses I, III-VIII. Frequencies vary up to a maximum of 5 per cent.

BOLIVINA SUBAENARIENSIS MEXICANA Cushman

(Plate 7, figure 33)

Bolivina subaenariensis Cushman var. *mexicana* Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 47, pl. 8, fig. 1.

The chief distribution is in traverses III, V-IX from 100 m. to 370 m. but there are scattered occurrences to 35 m. shoaler and 3250 m. deeper; traverses II, IV, X, XI have scattered occurrences. The highest frequencies are between 100 m. and 270 m. reaching a maximum of 32 per cent in III at 155 m.

BOLIVINA SUBSPINESCENS Cushman

(Plate 7, figures 30, 35)

Bolivina subspinescens Cushman, 1922, Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 48, pl. 7, fig. 5.

This species varies, as it does in the northwestern Gulf of Mexico, in the number of spines ornamenting the test and in the amount of undercutting of the chambers.

It is widely distributed in all traverses except I at all depths. Frequencies do not exceed 5 per cent.

BOLIVINA TRANSLUCENS Phleger and Parker

(Plate 7, figure 34)

Bolivina translucens Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 15, pl. 7, figs. 13, 14a, b.

This species occurs in traverses II, III, V-XI deeper than 145 m. The distribution is rather scattered and does not exceed 1 per cent in frequency.

BOLIVINA sp.

(Plate 7, figure 25)

This species although fairly widely distributed in the area never is very common. It is smaller, with less coarse perforations than *B. seminuda* Cushman, but in other respects is quite similar to that species.

It occurs in traverses VI-XI deeper than 420 m. Frequencies are less than 1 per cent.

LOXOSTOMUM ABRUPTUM Phleger and Parker

(Plate 7, figure 32)

Loxostomum truncatum Phleger and Parker, 1951 (not Finlay, 1947), Mem. Geol. Soc. America, vol. 46, pt. 2, p. 17, pl. 7, figs. 15-19.

Loxostomum abruptum Phleger and Parker, 1952, Contr. Cushman Found. Foram. Res., vol. 3, pt. 1, p. 14.

The resemblance of this species to *Bolivina minuta* Natland has been pointed out by Phleger *et al* (1953, p. 35). A study of additional specimens from the California coast shows that Natland's species is more regular with less highly raised sutures. The thicker, more twisted specimens mentioned by Phleger and Parker (1951) do not appear in the California material. The specimens from the Atlantic deep-sea cores are of this type.

The species occurs in all traverses but I and IV but most consistently in VI-XI. Most occurrences are deeper than 445 m. though there are scattered occurrences deeper than 100 m. Deeper than 580 m. frequencies may reach a maximum of 3 per cent; shoaler they are less than 1 per cent.

RECTOBOLIVINA ADVENA (Cushman)

(Plate 7, figure 27)

Siphogenerina advena Cushman, 1922, Carnegie Instit. Washington, Publ. 311, p. 35, pl. 5, fig. 2.

In referring this and the following species to the genus *Rectobolivina,* rather than to *Siphogenerina* as has been done by many authors, I am following the analyses of the two genera given by Hofker (1951 b, pp. 116, 232). The differences in internal structure seem to be borne out by differences in the external characters of the tests: *Rectobolivina* being compressed at least in the early portion of the test and usually throughout, *Siphogenerina* being often cylindrical, almost invariably non-compressed and costate. It seems probable that further analysis of the internal structure and chamber arrangement of the various species assigned to these genera will establish these external characters.

R. advena occurs in traverses IV-VIII, IX (once), XI (once) to a depth of 185 m. There are 3 deeper occurrences. Frequencies are usually less than 1 per cent.

RECTOBOLIVINA DIMORPHA (Parker and Jones)
(Plate 7, figure 37)

Uvigerina (*Sagrina*) *dimorpha* Parker and Jones, 1865, Philos. Trans. Roy. Soc. London, vol. 155, p. 364, pl. 18, fig. 18.

The reasons for referring this species to *Rectobolivina* are given under the previous species.

It occurs in traverses VI-VIII with single occurrences in IX and XI. The depth range is 345 m. to 1400 m. Frequencies are less than 1 per cent.

REUSSELLA ATLANTICA Cushman
(Plate 7, figure 28)

Reussella spinulosa (Reuss) var. *atlantica* Cushman, 1947, Contr. Cushman Lab. Foram. Res., vol. 23, pt. 4, p. 91, pl. 20, figs. 6, 7.

This species occurs in traverses IV-IX, XI to a depth of 235 m. There are two probably displaced occurrences deeper than 900 m. Frequencies reach a maximum of 8 per cent in V at 71 m.

UVIGERINA AUBERIANA d'Orbigny
(Plate 7, figure 38; Plate 8, figure 1)

Uvigerina auberiana d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, ''Foraminifères,'' p. 106, pl. 2, figs. 23, 24.

This and the following species are retained in the genus *Uvigerina*. There is some question in my mind of the necessity or practicality of the genera set up by Hofker (1951b) subdividing this genus. His genus *Alluvigerina* should be placed in the synonymy under *Uvigerina* since the two have the same genotype: *U. pigmea* d'Orbigny. Those interested in the subdivisions into which the Gulf of Mexico forms should be placed according to the Hofker classification will probably find this information in his forthcoming paper on the West Indian fauna.

As pointed out by Phleger *et al* (1953, p. 37), *U. auberiana* shows great variation in size. The species was described as 0.33 mm. in length by d'Orbigny. Gulf of Mexico specimens range from 0.30 mm.-1.0 mm.

This species occurs in traverses II, V-XI deeper than 250 m. Frequencies are usually less than 1 per cent. There is one occurrence of 9 per cent, and several between 1 and 3 per cent in traverses IX-XI.

UVIGERINA FLINTII Cushman
(Plate 8, figure 2)

Uvigerina flintii Cushman, 1923, Bull. U. S. Nat. Mus., vol.104, pt. 4, p. 165, pl. 42, fig. 13.

This species occurs in traverses VI-IX, XI from 85 m. to 420 m. Frequencies are never higher than 5 per cent.

UVIGERINA HISPIDO-COSTATA Cushman and Todd
(Plate 8, figure 3)

Uvigerina hispido-costata Cushman and Todd, 1945, Spec. Publ. no. 15, Cushman Lab. Foram. Res., p. 51, pl. 7, figs. 27, 31.

This species occurs in traverses VI-X from 220 m. to 1000 m. Frequencies vary up to 13 per cent.

UVIGERINA LAEVIS Goës
(Plate 8, figure 4)

Uvigerina auberiana Goës, 1882 (not d'Orbigny, 1839), Kongl. Svensk. Vet. Akad. Handl., vol. 19, no. 4, p. 60, pl. 4, figs. 71-74.

Uvigerina auberiana d'Orbigny var. *laevis* Goës, 1896, Bull. Mus. Comp. Zool., vol. 29, p. 51.

This species has been raised to specific rank as there seems to be no close relationship to *U. auberiana*. The wall of the test is much less rugose, the chambers less inflated and more elongate in shape, and the whole test relatively more elongate. Gulf of Mexico specimens have a maximum length of 0.6 mm. The maximum length given by Goës is 1.0 mm.

The distribution is in traverses V-XI with a single occurrence in IV. With a single exception occurrences are deeper than 80 m. The highest frequencies are between 160 and 275 m. reaching a maximum of 9 per cent. Shoaler than 90 m. and deeper than 915 m., frequencies are less than 1 per cent.

UVIGERINA PARVULA Cushman
(Plate 8, figure 6)

Uvigerina peregrina Cushman var. *parvula* Cushman, 1923, Bull. U. S. Nat. Mus., vol. 104, pt. 4, p. 168, pl. 42, fig. 11.

It is possible that more than one form has been included here in the population counts. There is considerable variation in the character of the costae which are much more numerous and finer in some specimens than in others. All these forms, however, are distinct from *U. peregrina* which usually is much larger, with higher plate-like costae, frequenly broken up into spines in the upper part of the test.

This species occurs in traverses III-IX, XI to a depth of 445 m. except in V where it extends to a depth of 914 m. Shoaler than 290 m. the frequencies are highest with a maximum of 9 per cent; deeper, they are usually less than 1 per cent.

UVIGERINA PEREGRINA Cushman
(Plate 8, figure 5)

Uvigerina peregrina Cushman, 1923, Bull. U. S. Nat. Mus., vol. 104, pt. 4, p. 166, pl. 42, figs. 7-10.

The Gulf of Mexico specimens are identical to topotypes from the northeastern coast of the United States.

This is a widely distributed species in all traverses but I and IV deeper than 200 m. (2 exceptions). Frequencies are relatively high to a depth of 1600 m. reaching a maximum of 25 per cent at 1144 m. in VI, although they are usually less than 20 per cent.

ANGULOGERINA BELLA Phleger and Parker
(Plate 8, figure 7)

Angulogerina bella Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 12, pl. 6, figs. 7, 8.

This species occurs in traverses III-V, VII, VIII to a depth of 235 m. In X and XI there are 3 occurrences deeper than 940 m. probably representing displaced specimens. Most frequencies are less than 1 per cent.

ANGULOGERINA JAMAICENSIS Cushman and Todd
(Plate 8, figure 8)

Angulogerina jamaicensis Cushman and Todd, 1945, Spec. Publ. no. 15, Cushman Lab. Foram. Res., p. 53, pl. 8, fig. 3.

Specimens were compared with the types by Miss Ruth Todd and found to be identical. The species has not been reported hitherto from Recent sediments.

It occurs in traverses I, IV-IX, XI with the chief occurrence in V-VII. The greatest abundance is shoaler than 150 m. but there are occurrences to a depth of 1750 m. Most frequencies are less than 1 per cent but a maximum of 4 per cent is reached shoaler than 150 m.

TRIFARINA BRADYI Cushman

(Plate 8, figure 9)

Trifarina bradyi Cushman, 1923, Bull. U. S. Nat. Mus., vol. 104, pt. 4, p. 99, pl. 22, figs. 3-9.

This species has a wide distribution in traverses V-XI at all depths. The most consistent occurrence is from 140 to 2150 m. Frequencies are variable reaching a maximum in IX of 8 per cent. Shoaler than 255 m. and deeper than 1900 m. they are always less than 1 per cent.

Family ROTALIIDAE

SPIRILLINA VIVIPARA Ehrenberg

(Plate 8, figures 15, 16)

Spirillina vivipara Ehrenberg, 1843 (1841), Abhandl. k. Akad. Wiss. Berlin, Theil. 1, pp. 323, 422, pl. 3, sec. 7, fig. 41.

This species occurs in traverses VI-VIII, XI to a depth of 285 m. There are three single occurrences, probably of displaced specimens, deeper than 914 m. in III, IX and X. All frequencies are less than 1 per cent.

CONORBINA ORBICULARIS (Terquem)

(Plate 8, figures 13, 14)

Rosalina orbicularis Terquem, 1876, Ess. Anim. Plage Dunkerque, pt. 2, p. 75, pl. 9, figs. 4a, b.

This species has a scattered occurrence in traverses VI-VIII, XI to a depth of 160 m., except for one occurrence at 225 m. Frequencies are less than 1 per cent.

"DISCORBIS" BULBOSA n. sp.

(Plate 8, figures 10, 11, 12)

Test small, globose, with a low spire, ventrally concave with an open umbilicus; chambers 8-12, 4 in the last-formed whorl, inflated; sutures curved, depressed; wall thin, often translucent, with coarse perforations; aperture simple, a high arch at the base of the last-formed chamber from the edge of the previous chamber to the periphery. Maximum diameter 0.25 mm.; thickness 0.18 mm.

Holotype from station 220, Lat. 29°49′ N, Long. 88°21′ W, at a depth of 37 m.

This species is referred to *Discorbis* pending further investigation of that genus and related ones. It is apparently not referable to any described genus as presently understood. It differs from *"D." subglobosa* Cushman in having 4 chambers in the last-formed whorl instead of 5, and in the higher spire.

"D." bulbosa occurs in traverses IV-VIII, XI to a depth of 205 m. Shoaler than 100 m. frequencies may be as high as 2 per cent; deeper, they are less than 1 per cent.

ROSALINA BERTHELOTI d'Orbigny

(Plate 8, figures 22, 23)

Rosalina bertheloti d'Orbigny, 1839, in Barker-Webb and Berthelot, Hist. Nat. Îles Canaries, vol. 2, pt. 2, "Foraminifères," p. 135, pl. 1, figs. 28-30 (*R. berthelotiana* in expl. of plate).

Hofker (1951a) has made this species the genotype of his genus *Discopulvinulina*. Since he later (Hofker, 1951b) includes in this genus *Rosalina globularis* d'Orbigny, designated as the genotype of *Rosalina* by Galloway and Wissler (1927, p. 62), *Discopulvinulina* becomes a synonym of *Rosalina* d'Orbigny, 1826.[1] *Rosalina* has been made a synonym of the genus *Discorbis* by many authors. As pointed out by Galloway and Wissler and later by Brotzen (1942, p. 15), the character of *Discorbis vesicularis* (Lamarck), the genotype of the genus, is very uncertain.

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[1] This presupposes that Hofker is correct in placing *R. bertheloti* and *R. globularis* in the same genus. This question is discussed by Hornibrook and Vella (1954, The Micropaleontologist, vol. 8, no. 1, p. 26).

This in itself is not sufficient to discard the name *Discorbis* as they maintain, but the figures of *D. vesicularis* obviously do not represent a form similar to the majority of species placed in that genus. Hence an entirely wrong concept of the genus *Discorbis* has been erected on a very shaky structure. It seems best not to speculate further on the real character of *D. vesicularis* and its place in the classification until the type is studied. The recent definition of *Discorbis* given by Bermudez (1952, p. 32) is not borne out by the figures of *D. vesicularis*. *Rosalina* appears to be closely related to *Cibicidina* Bandy and *Hanzawaia* Asano.

R. bertheloti occurs in traverses IV-VI, VIII-XI chiefly between the depths of 100 m. and 265 m. There are a few shoaler occurrences, and two deeper than 900 m. probably representing displaced specimens. Frequencies are usually less than 1 per cent occasionally as high as 3 per cent.

ROSALINA cf. CONCINNA (H. B. Brady)
(Plate 8, figures 17, 18)

Discorbina concinna H. B. Brady, 1884, Rept. Voy. CHALLENGER, Zool. vol. 9, p. 646, pl. 90, figs. 7, 8.

The specimens are very similar to Brady's figured ones and may be identical. They appear, however, to be bigger and more finely perforate, having a maximum diameter of 0.36 mm. Brady reports a diameter of 0.25 mm. The species differs from *R. columbiensis* (Cushman) in being less coarsely perforate, and having a more sharply angled periphery.

This species occurs chiefly in traverses IV-VIII, X, XI with a few occurrences in II, III, IX. It is abundant to a depth of 180 m. but has a scattered occurrence deeper. To a depth of 30 m. frequencies may be as high as 26 per cent, then decreasing until deeper than 235 m. where they are less than 1 per cent.

ROSALINA FLORIDANA (Cushman)
(Plate 8, figures 19, 20)

Discorbis floridanus Cushman, 1922, Publ. no. 311, Carnegie Instit. Washington, p. 39, pl. 5, figs. 11, 12.

This species occurs in traverses IV-VIII, IX (once), XI to a depth of 285 m. except in V where it extends to 915 m. A maximum frequency of 15 per cent occurs at the inner end of VI but in most cases frequencies do not exceed 5 per cent to a depth of 110 m.; deeper they are less than 1 per cent.

ROSALINA FLORIDENSIS (Cushman)

(Plate 8, figures 28, 29)

Discorbis bertheloti (d'Orbigny) var. *floridensis* Cushman, 1930, *in* Cushman and Jarvis, Journ. Pal., vol. 4, no. 4, p. 364, pl. 33, figs. 13a-c; 1931, Bull. U. S. Nat. Mus., vol. 104, pt. 8, p. 17, pl. 3, figs. 3-5.

Cushman's figured specimens (1931) are apparently identical with ours. The figures of the fossil species (1930) appear more finely perforate but the type has not been examined.

The distribution is scattered in traverses V-IX, XI from 40 to 180 m. with frequencies mostly less than 1 per cent.

ROSALINA PARKERAE (Natland)

(Plate 8, figures 24, 25)

Discorbis parkeri Natland, 1950, Mem. Geol. Soc. America, vol. 43, pt. 4, p. 27, pl. 6, figs. 11a-c.

Doubt is expressed by Phleger *et al* (1953, p. 40) of the validity of this species because suites of *R. williamsoni* (Parr) from the North Atlantic include specimens of this type. In the Gulf of Mexico, however, the specimens are all similar to Natland's species and do not range into the typical form of *R. williamsoni*.

R. parkerae occurs in all traverses but I-III at all depths. Frequencies are usually less than 1 per cent.

ROSALINA SUEZENSIS (Said)

(Plate 8, figures 21, 26, 27)

Discorbis suezensis Said, 1949, Spec. Publ. 26, Cushman Lab. Foram. Res., p. 36, pl. 3, fig. 34.

This species is similar to *R. candeiana* d'Orbigny but is much more finely perforate. Gulf of Mexico specimens resemble topotypes of *R. suezensis* from the Gulf of Suez. The specimens referred by Phleger and Parker (1951, p. 20) to *Discorbis candeiana* should be referred to Said's species.

R. suezensis occurs in traverses III-IX, XI (once). The most concentrated distribution is to 320 m. but there is scattered occurrence mostly in IX to 914 m. There are two occurrences deeper than 2300 m. Frequencies between 1 and 6 per cent occur to 200 m.; deeper, they are usually less than 1 per cent.

VALVULINERIA HUMILIS (H. B. Brady)

Truncatulina humilis H. B. Brady, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 665, pl. 94, figs. 7a-c.

This species is omitted from the population counts due to its small size and superficial resemblance to juvenile planktonic specimens. It is present at many deep-water stations in the area.

VALVULINERIA MEXICANA n. sp.

(Plate 9, figures 1, 2, 3)

Valvulineria cf. *araucana* (d'Orbigny), Phleger and Parker, 1951 (not *Rosalina araucana* d'Orbigny, 1839), Mem. Geol. Soc. America, vol. 46, pt. 2, p. 25, pl. 13, figs. 7a, b, 8a, b.

Test medium in size, biconvex but more so on the ventral side, periphery rounded; chambers 6-7 in the last-formed whorl of the adult, usually 13 in all excluding the proloculus, increasing fairly rapidly in size as added, later ones slightly inflated on the dorsal side, very much so on the ventral especially toward the umbilicus where they often have a bulbous protuberance, the last-formed chamber with a large flap extending over the umbilical area, the flap of the next-to-last chamber often visible below and to one side of it, the flaps of earlier chambers occasionally visible; sutures narrow but broader in the early portion, curved on the dorsal side, somewhat less so on the ventral, later ones slightly depressed on the dorsal side, more so on the ventral especially toward the umbilicus; wall thin, rather coarsely perforate, the perforations much less closely spaced on the early chambers and often only on the outer part of the chambers of the ventral side; aperture below the extended flap of the chamber. Maximum diameter 0.4 mm.

Holotype from station 31, Lat. 28°56′ N, Long. 88°46′ W, at a depth of 373 m.

This species resembles *V. nipponica* Ishizaki but differs in the non-keeled periphery of the early portion of the last-formed whorl and in the sutures of the early portion not being raised.

It is smaller than *V. palmerae* Cushman and Todd, with a less broadly rounded periphery, less inflated chambers, and less closely spaced perforations. The species referred by Phleger *et al* (1953, p. 40) to *V.* cf. *araucana* is not referable to *V. mexicana.*

This species has a very scattered distribution in traverses II, III, VII-IX, XI deeper than 75 m. Frequencies are usually less than 5 per cent but reach a maximum of 11 per cent in III at 400 m.

VALVULINERIA MINUTA n. sp.

(Plate 9, figures 4, 5, 6)

Test small, concavo-convex with a rounded periphery and a deep umbilicus on the ventral side; chambers 7 in the last-formed whorl, 11-13 in all excluding the proloculus, increasing gradually in size as added, slightly inflated, somewhat more so on the ventral side; the last-formed chamber with a small, narrow flap extending a short way into the umbilicus; sutures narrow, very slightly curved, later ones slightly depressed on the dorsal side, somewhat more so on the ventral; wall thin, finely perforate, aperture extending from the periphery, partially concealed by the chamber-flap. Maximum diameter 0.3 mm.

Holotype from station 184, Lat. 28°45′ N, Long. 86°02.5′ W, at a depth of 274 m.

This species differs from *V. araucana* (d'Orbigny) in its somewhat less convex dorsal side, deeper umbilicus, fewer chambers with less curving sutures on the dorsal side, and finer perforations.

V. minuta occurs in traverses V-XI at all depths deeper than 75 m. and in II and IV at a few scattered localities. All frequencies are less than 1 per cent.

GYROIDINOIDES SOLDANII ALTIFORMIS (R. E. and K. C. Stewart)

(Plate 9, figures 7,8)

Gyroidina soldanii d'Orbigny var. *altiformis* R. E. and K. C. Stewart, 1930, Journ. Pal., vol. 4, no. 3, p. 67, pl. 9, fig. 2.

This species occurs chiefly in traverses V-XI with single occurrences in II and III. With one exception all occurrences are deeper than 150 m. Frequencies are less than 1 per cent.

GYROIDINA NEOSOLDANII Brotzen
(Plate 9, figures 9, 10)

Rotalia soldanii H. B. Brady, 1884 (not *Gyroidina soldanii* d'Orbigny, 1826), Rept. Voy. CHALLENGER, Zool., vol. 9, p. 706, pl. 107, figs. 6, 7.

Gyroidina neosoldanii Brotzen, 1936, Sver. Geol. Unders., ser. C, no. 396, p. 158.

This species resembles *Gyroidinoides* in having its aperture extend into the umbilicus. In other respects it conforms more closely to *Gyroidina*. Specimens referred by Phleger *et al* (1953, p. 41) to *G. soldanii* var. are referable to *Gyroidinoides neosoldanii*.

The distribution is scattered in traverses III, VI, VIII-XI chiefly in IX-XI. All occurrences are deeper than 185 m. Frequencies are less than 1 per cent.

GYROIDINA ORBICULARIS d'Orbigny
(Plate 9, figures 13, 18)

Gyroidina orbicularis d'Orbigny, 1826, Ann. Sci. Nat., ser. 1, vol. 7, p. 278; Modèles, no. 13.

This is a widely distributed species in all traverses but I and IV, deeper than 165 m. Frequencies are less than 1 per cent to 585 m.; deeper, they are usually 1-5 per cent.

EPONIDES ANTILLARUM (d'Orbigny)
(Plate 9, figures 14, 15)

Rotalina antillarum d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 75, pl. 5, figs. 4-6.

This species has "sutural" foramina which according to Hofker (1951b) would place it in the genus *Gyroidina*. It is retained in *Eponides* for the reasons given under *E. repandus* (Fichtel and Moll).

E. antillarum occurs in traverses IV-VIII to a depth of 145 m. Frequencies are variable with a maximum of 9 per cent in V at 44 m.

EPONIDES POLIUS Phleger and Parker
(Plate 9, figures 11, 12)

Eponides polius Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 21, pl. 11, figs. 1a, b, 2a, b.

This species has "sutural" foramina which according to Hofker (1951b) would place it in *Gyroidina* (*vide E. repandus*).

It occurs in all traverses but I and IV deeper than 585 m. Frequencies vary to a maximum of 5 per cent except in II where they reach a maximum of 8 per cent at 2788 m.

EPONIDES REGULARIS Phleger and Parker
(Plate 9, figures 16, 17)

Eponides regularis Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 21, pl. 11, figs. 3a, b, 4a-c.

This species has "sutural" foramina which according to Hofker (1951b) would place it in the genus *Gyroidina* (*vide E. repandus*).

It occurs in traverses II, III, V-VII from 145 m. to 3000 m. Most frequencies are from 1-5 per cent but in III a maximum of 21 per cent occurs at 205 m.

EPONIDES REPANDUS (Fichtel and Moll)
(Plate 9, figures 27, 28)

Nautilus repandus Fichtel and Moll, 1803, Test. Micr., p. 35, pl. 3, figs. a-d.

Examination of specimens from the Mediterranean and Gulf of Mexico show that the foramina are "sutural" rather than "areal" as shown by Hofker (1951b, p. 332) for specimens from Siboga material. "Sutural" foramina according to Hofker are a characteristic of the genus *Gyroidina* as contrasted to *Eponides* whose foramina are "areal." Since *Eponides repandus* is the genotype of *Eponides,* Hofker's classification is not used here pending further study.

E. repandus occurs in traverses V-IX, XI, to a depth of 185 m. Most frequencies are less than 1 per cent, occasionally higher.

EPONIDES TUMIDULUS (H. B. Brady)
(Plate 9, figures 19, 24)

Truncatulina tumidula H. B. Brady, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 666, pl. 95, figs. 8a-d.

This species occurs chiefly in traverses II, IX-XI with scattered occurrences in III, V, VI. Frequencies vary up to 5 per cent.

EPONIDES TURGIDUS Phleger and Parker
(Plate 9, figures 22, 23)

Eponides turgidus Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 22, pl. 11, figs. 9a, b.

This species has "sutural" foramina which according to Hofker's (1951b) classification would place it in the genus *Gyroidina* (*vide E. repandus*).

It is widely distributed in all traverses but I and IV at all depths. Frequencies shoaler than 175 m. are less than 1 per cent; 1-5 per cent mostly to 1500 m.; deeper than 1500 m. a maximum of 22 per cent is reached in III at 2388 m. and frequencies are often 5-20 per cent.

PSEUDOEPONIDES UMBONATUS (Reuss)
(Plate 9, figures 20, 21)

Rotalina umbonata Reuss, 1851, Zeitschr. deutsch. Geol. Ges., vol. 3, p. 75, pl. 5, figs. 35a-c.

Supplementary apertures are frequently observed on the dorsal side of the specimens but the ventral ones described by Uchio (1953, p. 157) are obscure. Small specimens possibly referable to *Eponides tenera* (H. B. Brady) are included with this species in the population counts. Supplementary apertures were not observed in these specimens.

These forms are widely distributed in all traverses but I and IV. Frequencies are less than 1 per cent to a depth of 875 m.; deeper they are often 1-5 per cent.

BUCCELLA HANNAI (Phleger and Parker)
(Plate 9, figures 25, 26)

Eponides hannai Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 21, pl. 10, figs. 11a, b, 12a, b, 13a, b, 14a, b.

This species occurs in traverses IV-VIII to a depth of 185 m. Frequencies to 40 m. are usually 1-2 per cent; deeper they are less than 1 per cent.

OSANGULARIA CULTUR (Parker and Jones)
(Plate 9, figures 29, 30)

Planorbulina cultur Parker and Jones, 1865, Philos. Trans. Roy. Soc. London, vol. 155, p. 421, pl. 19, fig. 1.

This species occurs in all traverses but I and IV deeper than 400 m. Frequencies are 1-5 per cent to a depth of 2000 m.; deeper they are usually less than 1 per cent.

"ROTALIA" BECCARII (Linné) variants

(Plate 10, figures 1, 2, 5, 6)

Nautilus beccarii Linné, 1758, Syst. Nat. ed. 10, p. 710.

The variants of this species are lumped together here as they are all confined to very shallow water in the area and do not show any individual distributions in the open-ocean environment represented here. A finer grid of sampling might reveal a more variable distribution.

The distribution is in traverses I-VIII shoaler than 125 m. At the inner ends of the traverses frequencies may be as high as 34 per cent but quickly reduce to 1-5 per cent, and in most cases deeper than 70 m. are less than 1 per cent.

"ROTALIA" TRANSLUCENS Phleger and Parker

(Plate 10, figures 3, 7)

"Rotalia" translucens Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 24, pl. 12, figs. 11a, b, 12a, b.

This is a widely distributed species in all traverses but I. It usually occurs deeper than 220 m. but there are occurrences as shoal as 60 m. Frequencies from 220 to 735 m. are often 5-20 per cent with a maximum of 27 per cent. Deeper than 735 m. they do not exceed 5 per cent and decrease until deeper than 1700 m. where they are usually less than 1 per cent.

HÖGLUNDINA ELEGANS (d'Orbigny)

(Plate 10, figures 4, 8)

Rotalia (Turbulina) elegans d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 276, no. 54.

This is a widely distributed species in traverses II, V-XI deeper than 65 m. Frequencies are less than 1 per cent to a depth of 345 m.; 1-5 per cent deeper, with a few higher frequencies deeper than 1300 m. The maximum is 25 per cent in X at 2150 m.

SIPHONINA BRADYANA Cushman
(Plate 10, figures 9, 10)

Siphonina bradyana Cushman, 1927, Proc. U. S. Nat. Mus., vol. 72, art. 20, p. 11, pl. 1, figs. 4a-c.

This species occurs in traverses VI-XI from 45 m. to 650 m. The occurrence in X is a single one at 950 m. Most frequencies are less than 1 per cent.

SIPHONINA PULCHRA Cushman
(Plate 10, figures 11, 12)

Siphonina pulchra Cushman, 1919, Carnegie Instit. Washington, Publ. 291, p. 42, pl. 14, figs. 7a-c.

The distribution is chiefly in traverses V-IX, XI to a depth of 640 m. There is a single occurrence in II at 2000 m. probably representing displacement. Most frequencies are less than 1 per cent with a few as high as 2 per cent between 100 and 300 m.

CANCRIS OBLONGA (Williamson)
(Plate 10, figures 13, 14)

Rotalina oblonga Williamson, 1858, Rec. Foram. Great Britain, p. 51, pl. 4, figs. 98-100.

Included in the population counts with this species are specimens of *Cancris sagra* (d'Orbigny) (Plate 10, figures 15, 21). The two species appear to have the same overall distribution.

The distribution is in traverses I (once), IV-XI to a depth of 255 m. There are a few occurrences deeper than 915 m. in X and XI probably representing displaced specimens. Frequencies are less than 1 per cent except between 35 m. and 145 m. where they reach a maximum of 2 per cent.

Family AMPHISTEGENIDAE

ASTERIGERINA CARINATA d'Orbigny
(Plate 10, figures 16, 17)

Asterigerina carinata d'Orbigny, 1839, in De la Sagra, Hist. Phys. Pol. Nat. Cuba, "Foraminifères," p. 118, pl. 5, fig. 25; pl. 6, figs. 1, 2.

This species occurs in traverses IV-VIII, XI (once) to a depth of 185 m. Frequencies shoaler than 85 m. are high, reaching a maximum of 31 per cent although frequently much lower. Deeper than 100 m. they are usually less than 1 per cent.

AMPHISTEGINA spp.

It is probable that most, or all, of the specimens are referable to *A. lessonii* d'Orbigny but owing to the weathered condition of many of them it is impossible to be sure.

The distribution is in traverses IV-XI to a depth of 240 m. though the main occurrence is not deeper than 150 m. There are a few occurrences in XI deeper than 1700 m. probably representing displaced specimens. Frequencies shoaler than 200 m. vary to a maximum of 50 per cent although usually less than 20 per cent; deeper they are less than 1 per cent.

Family CASSIDULINIDAE

EPISTOMINELLA DECORATA (Phleger and Parker)

(Plate 10, figures 18, 19)

Pseudoparrella decorata Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 28, pl. 15, figs. 4a, b, 5a, b.

This is a deep-water species occurring in all traverses but I and IV usually deeper than 1000 m. though with a few occurrences as shoal as 820 m. and single occurrences at 155 m. and 600 m. Frequencies deeper than 1100 m. are high, usually over 5 per cent and reaching a maximum of 22 per cent.

EPISTOMINELLA EXIGUA (H. B. Brady)

(Plate 10, figures 22, 23)

Pulvinulina exigua H. B. Brady, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 696, pl. 103, figs. 13, 14.

This is a widely distributed species in all traverses but I and IV deeper than 220 m. Frequencies are usually high especially between 550 m. and 960 m. where they reach a maximum of 16 per cent. Outside these limits they do not exceed 5 per cent and deeper than 1400 m. are often less than 1 per cent.

EPISTOMINELLA RUGOSA (Phleger and Parker)

(Plate 10, figures 24, 25)

Pseudoparrella rugosa Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 28, pl. 15, figs. 8a, b, 9a, b.

This species occurs chiefly in traverses V-XI, with single occurrences in II and III; deeper than 250 m. most frequencies are 1-4 per cent except in IX where they are 11 per cent at 320-421 m.

EPISTOMINELLA VITREA Parker
(Plate 10, figures 20, 26)

Epistominella vitrea Parker, *in* Parker, Phleger and Peirson, 1953, Spec. Publ. 2, Cushman Found. Foram. Res., p. 9, pl. 4, figs. 34-36, 40, 41.

Some of the specimens referred to *E. exigua* by Phleger and Parker (1951, p. 28) may be referable to *E. vitrea.*

This species is widely distributed in traverses III-XI with a single occurrence in II. It is found at all depths. Shoaler than 100 m. frequencies are variable reaching a maximum of 34 per cent; deeper, they are usually less than 1 per cent.

STETSONIA n. gen.

Genotype: *Stetsonia minuta* n. sp.

Test calcareous, perforate, slightly trochoid; almost completely involute; aperture elongate in the apertural face, in the plane of coiling, slightly ventral of the periphery.

This genus is closely related to *Epistominella* but differs in being almost completely involute. In the genotype one or two chambers of the second whorl are sometimes visible on the dorsal side. The genus is at present monotypic so that variations of the amount of test which may be evolute cannot be delimited here, except to say that the chambers are not all visible on the dorsal side, as in *Epistominella,* and probably that only a small amount of the second whorl might be visible. This genus is considered to have developed from *Epistominella* and is at present unknown as fossil.

STETSONIA MINUTA n. sp.
(Plate 10, figures 27, 28, 29)

Test small, compressed, with a narrowly rounded periphery; chambers 8 or 9 in the last-formed whorl, very slightly inflated; sutures slightly curved, slightly depressed; wall thin, somewhat translucent, finely perforate; aperture elongate, narrow, slightly ventral of the periphery, with a narrow lip. Maximum diameter: 0.18 mm.

Holotype from station 218, Lat. 29°40′ N, Long. 88°28.5′ W, at a depth of 42 m.

This species is usually completely involute, but occasionally one or two chambers of the second whorl are visible on the dorsal side. Its involute character differentiates it from species of the genus *Epistominella* to which it is most closely related.

This species occurs in all traverses but I at all depths. Frequencies are usually less than 1 per cent.

CASSIDULINA CARINATA Silvestri
(Plate 10, figure 30)

Cassidulina laevigata d'Orbigny var. *carinata* Silvestri, 1896, Accad. Pont. N. Lincei, Mem. 12, p. 104, pl. 2, fig. 10.

Gulf of Mexico specimens are very similar to those from the Pliocene of Siena, Italy, but have a larger clear area in the center. This is true also of specimens observed from the North Atlantic.

This species has a rather scattered occurrence in traverses III, V-X at all depths. Frequencies are variable up to a maximum of 17 per cent. They are usually much lower, not exceeding 5 per cent and often less than 1 per cent.

CASSIDULINA aff. CRASSA d'Orbigny
(Plate 10, figure 31)

Cassidulina crassa d'Orbigny, 1839, Voy. Amer. Mérid., vol. 5, pt. 5, ''Foraminifères,'' p. 56, pl. 7, figs. 18-20.

The specimens found in this area are less compressed and more lobulate than that figured by Brady (1884, pl. 54, fig. 5). The species as it occurs in the northwestern Gulf of Mexico conforms more closely to Brady's interpretation of d'Orbigny's species.

The distribution is chiefly in traverses VI-XI, with a few occurrences in II, III, V, deeper than 135 m. Frequencies are usually less than 1 per cent, shoaler than 500 m. sometimes 1-4 per cent.

CASSIDULINA CURVATA Phleger and Parker
(Plate 11, figure 1)

Cassidulina curvata Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 26, pl. 14, figs. 5a, b.

This species occurs in traverses II (twice), V-XI, at all depths deeper than 60 m. except for one occurrence at 35 m. To a depth of 600 m. frequencies are usually 1-5 per cent; deeper, they are less than 1 per cent.

CASSIDULINA LAEVIGATA d'Orbigny
(Plate 11, figure 2)

Cassidulina laevigata d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 282, no. 1, pl. 15, figs. 4, 5; Modèles, no. 41.

This species has a scattered distribution in traverses V-VIII, X, XI. Frequencies are less than 1 per cent except for a few shoaler than 150 m. which reach a maximum of 6 per cent.

CASSIDULINA NEOCARINATA Thalmann
(Plate 11, figure 3)

Cassidulina laevigata d'Orbigny var. *carinata* Cushman, 1922, (not Silvestri, 1896), Bull. U. S. Nat. Mus., vol. 104, pt. 3, p. 124, pl. 25, figs. 6, 7.

Cassidulina neocarinata Thalmann, 1950, Contr. Cushman Found. Foram. Res., vol. 1, pts. 3, 4, p. 44.

This species occurs in traverses II, V-XI, deeper than 75 m. Between 120 and 600 m. frequencies are usually 1 per cent or more reaching a maximum of 11 per cent. Deeper than 600 m. they are usually less than 1 per cent. The occurrences deeper than 950 m. are very scattered.

CASSIDULINA SUBGLOBOSA H. B. Brady and variants
(Plate 11, figures 4, 5, 6, 7, 8, 9)

Cassidulina subglobosa H. B. Brady, 1881, Quart. Journ. Micr. Sci., n. s., vol. 21, p. 60; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 430, pl. 54, figs. 17a-c.

There are several variants present in the area, as well as the typical form (Pl. 11, figs. 4, 5). A small compressed variant (Pl. 11, fig. 6) is similar to var. *depressa* Asano and Nakamura, and has a widespread distribution. A small globose form (Pl. 11, figs. 8, 9) with a sharply curved aperture in the juvenile specimens resembles var. *horizontalis* Cushman and Renz. This form and the large typical specimens seem to occur in deep water only. All these variants appear to merge into one another, and since in counting it was impossible to always differentiate them accurately it seemed best not to attempt to do so.

This is a very abundant, widely distributed group occurring in all traverses but I although chiefly in V-XI. Deeper than about 80 m. frequencies are usually between 5 and 20 per cent (maximum 23 per cent); deeper than about 2300 m. frequencies are often less than 5 per cent.

CASSIDULINOIDES TENUIS Phleger and Parker
(Plate 11, figure 14)

Cassidulinoides tenuis Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 27, pl. 14, figs. 14a, b, 15-17.

This species occurs in traverses II (twice), VI-XI, deeper than 255 m. Deeper than 1100 m. occurrences are very scattered. All frequencies are less than 1 per cent.

EHRENBERGINA SPINEA Cushman
(Plate 11, figure 12)

Ehrenbergina spinea Cushman, 1935, Smithsonian Misc. Coll., vol. 91, no. 21, p. 8, pl. 3, figs. 10, 11.

This species occurs only in traverses IX-XI. Four occurrences are between 135 m. and 255 m., and two are at 914 m. and 950 m. The occurrences between 139 m. and 155 m. have frequencies of 3-6 per cent, the others are less than 1 per cent. The deep occurrences probably represent displaced specimens.

Family CHILOSTOMELLIDAE

ROTAMORPHINA LAEVIGATA (Phleger and Parker)
(Plate 11, figures 10, 11)

Valvulineria laevigata Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 25, pl. 13, figs. 11a, b, 12a, b.

Eponides exigua Cushman, 1931 (not *Pulvinulina exigua* H. B. Brady, 1884), Bull. U. S. Nat. Mus., vol. 104, pt. 8, p. 44, pl. 10, figs. 1, 2.

Valvulineria sp. Parker, 1948, Bull. Mus. Comp. Zool., vol. 100, no. 2, p. 240, pl. 4, figs. 13a, b.

This species occurs in all traverses but I and IV, but chiefly in V-XI, deeper than 100 m. Frequencies are usually less than 1 per cent.

CHILOSTOMELLA OOLINA Schwager
(Plate 11, figure 15)

Chilostomella oolina Schwager, 1878, Boll. Com. Geol. Ital., vol. 9, p. 527, pl. 1, fig. 16.

This species occurs in traverses II, III, V-VIII, X (twice), XI (once), deeper than 125 m. Frequencies are usually less than 1 per cent but occasionally as high as 2 per cent.

SEABROOKIA EARLANDI Wright
(Plate 11, figure 13)

Seabrookia earlandi Wright, 1891, Proc. Roy. Irish Acad., ser. 3, vol. 1 (1889-91), no. 4, p. 477, pl. 20, figs. 6, 7.

This species occurs in traverses IV (once), V-XI at all depths but chiefly 100-2300 m. Frequencies are less than 1 per cent.

PULLENIA BULLOIDES (d'Orbigny)
(Plate 11, figure 17)

Nonionina bulloides d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 293; 1846, Foram. Bass. Tert. Vienne, p. 107, pl. 5, figs. 9, 10.

This is a widely distributed species in all traverses but I and IV, deeper than 145 m. Shoaler than 900 m. frequencies are less than 1 per cent; deeper, they may be as high as 2 per cent.

PULLENIA QUINQUELOBA (Reuss)
(Plate 11, figure 16)

Nonionina quinqueloba Reuss, 1851, Zeitschr. deutsch. Geol. Ges., vol. 3, p. 71, pl. 5, fig. 31.

This species occurs in all traverses but I and IV, deeper than 100 m. Shoaler than 530 m. all frequencies are less than 1 per cent; deeper, they may be as high as 2 per cent.

PULLENIA sp.
(Plate 11, figures 20, 24)

This is a small species with a maximum diameter of 0.3 mm. It is compressed with a narrowly rounded periphery and has seven chambers in the last-formed whorl. It most closely resembles *P. trinitatensis* Cushman and Stainforth but is smaller and more compressed, especially in the initial portion. It is probably a new species but there is not sufficient material to describe it adequately.

It occurs in traverses II, III (once), VI (once), VII (once), VIII-XI, deeper than 960 m. Frequencies are less than 1 per cent except in II where they are 2-3 per cent from 1900 m. to 2800 m.

SPHAEROIDINA BULLOIDES d'Orbigny
(Plate 11, figure 18)

Sphaeroidina bulloides d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 267, no. 1; Modèles, no. 65.

This is a widely distributed species in all traverses but I and IV, deeper than 100 m. Between 180 m. and 1000 m. frequencies are usually 1-5 per cent but reach a maximum of 9 per cent in II at 314 m. Outside these limits they are less than 1 per cent.

SPHAEROIDINA COMPACTA Cushman and Todd
(Plate 11, figure 19)

Sphaeroidina compacta Cushman and Todd, 1949, Contr. Cushman Lab. Foram. Res., vol. 25, pt. 1, p. 19, pl. 4, figs. 14a, b.

This species has a very scattered distribution from 120 m. to 3250 m. in traverses II, VI, VIII, X, XI. Frequencies are less than 1 per cent.

Family ANOMALINIDAE

ANOMALINOIDES MEXICANA n. sp.
(Plate 11, figures 21, 22, 23)

Test small, biconvex, involute, ratio of width to length 3: 4, periphery broadly rounded, non-lobulate in early portion, slightly lobulate in later portion of the test; chambers 7 or 8 in last-formed whorl, non-inflated in the early portion, last-formed one or two in the adult slightly inflated; sutures narrow, flush with the test except for the last ones in the adult which are slightly depressed, slightly curved; wall thin, somewhat translucent, finely but conspicuously perforate; aperture extending from the umbilicus to the periphery on the ventral side, with a distinct lip. Maximum diameter 0.4 mm.

Holotype from station 184, Lat. 28°45′ N, Long. 86°02.5′ W, at a depth of 274 m.

This species has fewer chambers than *A. plummerae* Brotzen, is more finely perforate, has non-elevated sutures in the early portion of the test, and is not round in outline.

A. mexicana occurs in traverses II (once), III (once), V-X, XI (once) deeper than 220 m. Frequencies are less than 1 per cent.

PLANULINA ARIMINENSIS d'Orbigny
(Plate 11, figure 27, 30)

Planulina ariminensis d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 280, no. 1, pl. 14, figs. 1-3 bis; Modèles, no. 49.

This species occurs in traverses V (once), VI-XI from 155 m. to 2550 m. Deeper than 740 m. the occurrence is very scattered. Frequencies are usually less than 1 per cent; the maximum frequency is 4 per cent.

PLANULINA EXORNA Phleger and Parker
(Plate 11, figures 28, 29)

Planulina exorna Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 32, pl. 18, figs. 5a, b, 6a, b, 7a, b, 8a, b.

This is a very abundant shallow-water species. It occurs in traverses II (once), IV-IX, XI (once) to a depth of 255 m., except in VIII where it extends to 365 m. At less than 100 m. frequencies are greatest reaching a maximum of 43 per cent, but usually less than 20 per cent. They decrease seaward until deeper than 150 m. where they are less than 1 per cent.

PLANULINA FOVEOLATA (H. B. Brady)
(Plate 11, figures 25, 26)

Anomalina foveolata H. B. Brady, 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 674, pl. 94, figs. 1a-c.

This species occurs in traverses II (once), V-IX, XI, from 75 m. to 345 m. except in V where it extends to 530 m. Frequencies from 120 m. to 270 m. may be as high as 5 per cent; elsewhere they are less than 1 per cent.

LATICARININA PAUPERATA (Parker and Jones)
(Plate 12, figure 3)

Pulvinulina repanda var. *menardii* subvar. *pauperata* Parker and Jones, 1865, Philos.Trans., Roy. Soc. London, vol. 155, p. 395, pl. 16, figs. 50, 51.

This species occurs in all traverses but I and IV, deeper than 255 m. Most frequencies are less than 1 per cent but deeper than 915 m. they may be as high as 2 per cent.

CIBICIDES CORPULENTUS Phleger and Parker

(Plate 12, figures 4, 8)

Cibicides robustus Phleger and Parker, 1951 (not Le Calvez, 1949), Mem. Geol. Soc. America, vol. 46, pt. 2, p. 31, pl. 17, figs. 1a, b, 2a, b, 3a, b, 4a, b.

Cibicides corpulentus Phleger and Parker, 1952, Contr. Cushman Found. Foram. Res., vol. 3, pt. 1, p. 14.

This species occurs in all traverses but I and IV, chiefly in V-XI, from 100 m. to 1800 m. There is a single occurrence at about 3000 m. Frequencies are less than 1 per cent.

CIBICIDES DEPRIMUS Phleger and Parker

(Plate 12, figures 1, 2)

Cibicides deprimus Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 29, pl. 15, figs. 16a, b, 17a, b.

This species occurs in traverses IV-XI to a depth of 915 m. with a few scattered occurrences to 2600 m. Shoaler than 150 m. frequencies are usually 1-5 per cent but reach a maximum of 19 per cent; deeper, they are less than 1 per cent.

CIBICIDES aff. FLORIDANUS (Cushman)

(Plate 12, figures 5, 9)

Truncatulina floridana Cushman, 1918, Bull. U. S. Geol. Surv., vol. 676, p. 62, pl. 19, fig. 2.

This species as defined here includes the same range of varying forms as occurs in the northwestern Gulf of Mexico. Included also are forms which were designated by Phleger and Parker (1951, p. 32, pl. 17, figs. 10, 11) as *Cibicides* sp. 1. The variant forms are not all figured here but may be found in Phleger and Parker (1951, pl. 16, figs. 1-4).

This is a widely distributed group in all traverses but I and IV from 35 m. to 1750 m. with a single occurrence at 2150 m. Frequencies are usually 1-5 per cent. Deeper than 1400 m. and shoaler than 60 m. they are less than 1 per cent.

CIBICIDES IO Cushman
(Plate 12, figures 6, 7)

Cibicides pseudoungeriana (Cushman) var. *io* Cushman (part), 1931, Bull. U. S. Nat. Mus., vol. 104, pt. 8, p. 125, pl. 23, fig. 1 (not fig. 2).

As has been stated previously by Phleger and Parker (1951, p. 30), Cushman has figured two species under this name. Figure 2 in the above reference was erroneously labelled the holotype in the explanation of plates. Figure 1 represents the holotype as shown by its catalogue number and the designation given by Cushman in the text.

This species occurs in traverses V-VIII from 50 to 150 m. Frequencies are usually less than 1 per cent.

CIBICIDES KULLENBERGI Parker
(Plate 12, figures 10, 11)

Cibicides kullenbergi Parker, 1953, in Phleger, Parker and Peirson, Repts. Swedish Deep-Sea Exped., vol. 7, no. 1, p. 49, pl. 11, figs. 7, 8.

This species has scattered occurrences in traverses II, III, V and more consistent ones in VI-XI deeper than 580 m., with the greatest deeper than 1000 m. Frequencies are usually less than 1 per cent but may be as high as 2 per cent.

CIBICIDES MOLLIS Phleger and Parker
(Plate 12, figures 12, 15)

Cibicides mollis Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 30, pl. 16, figs. 7a, b, 8a, b, 9a, b.

This species occurs in traverses V-VIII, XI from 50 to 185 m. There is a single occurrence at about 455 m. Frequencies are less than 1 per cent.

CIBICIDES PROTUBERANS n. sp.
(Plate 12, figures 13, 14, 16)

Test large, plano-convex, with 3-3½ whorls, lobulate in the adult and often very irregular in outline, regular in juvenile specimens, periphery keeled in the early chambers, later narrowly rounded, with a clear protuberant umbo; chambers 8-12 in the adult whorl; sutures slightly limbate in the early portion, later depressed, curved; wall thin, somewhat translucent, with large to medium perforations sometimes very closely spaced and sometimes irregularly scattered; aperture peripheral extending for a short distance on the evolute side. Maximum diameter 1.3 mm.

Holotype from station 116, Lat. 25°43′ N, Long. 84°13′ W, at a depth of 155 m.

This species most closely resembles *C. fletcheri* Galloway and Wissler but is larger, less convex on the involute side, and has a more protuberant umbo.

C. protuberans occurs in traverses IV-XI to a depth of 1850 m. The lower range is progressively deeper to the east: in IV, 42 m.; in V, 100 m.; in VI, 183 m.; in VII, 878 m.; in VIII, 585 m.; in IX, 420 m.; in X, 1317 m.; in XI, 1829 m. Deep occurrences in X and XI and possibly elsewhere probably represent displaced specimens. Shoaler than 200 m. frequencies are variable with a maximum of 21 per cent. They decrease deeper, and below 320 m. are less than 1 per cent.

CIBICIDES ROBERTSONIANUS (H. B. Brady)
(Plate 13, figures 2, 5)

Truncatulina robertsonianus H. B. Brady, 1881, Quart. Journ. Micr. Sci., vol. 21, p. 65; 1884, Rept. Voy. CHALLENGER, Zool., vol. 9, p. 664, pl. 95, figs. 4a-c.

In traverses II and III this species occurs deeper than 1200 m.; in V deeper than 914 m.; in VI-IX deeper than 275-585 m.; in X deeper than 950 m., and in XI deeper than 155 m. Deeper than 1000 m. frequencies are usually 1-5 per cent; shoaler they are usually less than 1 per cent.

CIBICIDES RUGOSA Phleger and Parker
(Plate 13, figures 1, 4)

Cibicides rugosa Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 31, pl. 17, figs. 5a, b, 6a, b.

This species occurs in traverses II (once), V-XI, from 575 m. to 2650 m. Frequencies are less than 1 per cent.

CIBICIDES UMBONATUS Phleger and Parker
(Plate 12, figure 17, 18)

Cibicides umbonatus Phleger and Parker, 1951, Mem. Geol. Soc. America, vol. 46, pt. 2, p. 31, pl. 17, figs. 7a, b, 8a, b, 9a, b.

This species occurs in traverses V-IX, from 35 m. to 600 m.

There is one occurrence in XI at 914 m. probably representing displacement. Frequencies shoaler than 150 m. and deeper than 550 m. are less than 1 per cent; between these limits they may be as high as 5 per cent.

CIBICIDES WUELLERSTORFI (Schwager)

(Plate 13, figure 3, 6)

Anomalina wuellerstorfi Schwager, 1866, Novara Exped., Geol. Theil., vol. 2, p. 258, pl. 7, figs. 105, 107.

I have previously referred this species to the genus *Planulina*. Since, however, it has an involute and an evolute side instead of being almost completely planispiral, it seems more logical to place it in *Cibicides*.

It occurs in all traverses but I and IV deeper than 800 m. except in traverses VII and VIII where it occurs deeper than 455 m. and 580 m. respectively. Deeper than 1000 m. frequencies are usually greater than 5 per cent and may be as high as 47 per cent; elsewhere they are usually 1-5 per cent but occasionally higher or lower.

CIBICIDINA STRATTONI (Applin)

(Plate 13, figures 8, 11)

Truncatulina americana Cushman var. *strattoni* Applin, 1925, *in* Applin, Ellisor and Kniker, Bull. Amer. Assoc. Petr. Geol., vol. 9, no. 1, p. 99, pl. 3, fig. 3.

C. concentrica (Cushman) (Plate 13, figures 7, 10) is often found occurring with this species but seldom in as great abundance. The two species appear to have the same distribution and have been combined in the population counts.

O. L. Bandy has pointed out to me (personal communication) that the genus *Cibicidina* is probably synonymous with *Hanzawaia* Asano. I have previously pointed out its resemblance also to *Rosalina* d'Orbigny.

The distribution is in traverses III (once), IV-VIII, IX (twice), XI (once) to a depth of 150 m. with a scattered occurrence to 235 m. There is a single occurrence at 914 m. in IX probably representing displacement. Frequencies at less than 100 m. are usually greater than 1 per cent, frequently greater than 5 per cent, and may be as high as 35 per cent. Deeper, frequencies decrease until at 150 m. they are less than 1 per cent.

Family PLANORBULINIDAE

PLANORBULINA MEDITERRANENSIS d'Orbigny
(Plate 13, figure 9)

Planorbulina mediterranensis d'Orbigny, 1826, Ann. Sci. Nat., vol. 7, p. 280, no. 2, pl. 14, figs. 4-6 bis.; Modèles, no. 79.

This species occurs in traverses IV (once), V-XI to a depth of 185 m. There are two occurrences in XI deeper than 1300 m. probably indicating displacement. Frequencies are usually less than 1 per cent.

GYPSINA VESICULARIS (Parker and Jones)
(Plate 13, figure 12)

Orbitolina vesicularis Parker and Jones, 1860, Ann. Mag. Nat. Hist., ser. 3, vol. 6, p. 31, no. 5.

This species occurs in traverses VI-VIII, XI to a depth of 155 m. Frequencies are less than 1 per cent.

CONCLUSIONS

1. Five faunal depth facies boundaries occur at: 80-100 m., 130-150 m., 180-220 m., 350-600 m., and 900-1000 m. There are less distinct boundaries at 30-50 m. and 250 m. Deeper than 1000 m. there are various changes which are not concentrated at particular depths. Salinity and temperature data show changing conditions with depth and may contribute to differentiation of facies.

2. Lateral changes from west to east are marked in facies 1-4. Factors affected by the outflow of the Mississippi River including turbidity, light penetration, food supply and the chemistry of the water and sediments are probably an important influence on faunas in traverses in that area. The increase to the east of the West Indian fauna is marked and the fauna of the continental shelf appears to be largely residual. In facies 5 and 6 lateral changes are less marked.

3. Displaced specimens from shallow stations occur at deep stations especially below the escarpment running north and south along the coast of Florida.

4. Most species present in significant frequencies are represented by living specimens at stations shoaler than 200 m.; at greater depths the presence of living specimens is irregular. There appears to be an analogy in the Mississippi Delta region between the percentage of total population found living and the rate of sedimentation.

5. Planktonic populations show similar distributions in the various traverses. They combine elements of North Atlantic mid- and low-latitude faunas. The extreme annual range of surface temperatures may partially explain this. To explain the presence of *Globigerina inflata* d'Orbigny and *G. pachyderma* (Ehrenberg), an east to west coastal current along the Florida coast is postulated. Other species may be introduced from the Caribbean.

6. Planktonic faunas compose less than 10 per cent of the total population shoaler than 100 m. and 90 per cent or more deeper than 1000 m. They do not appear in the shallow stations most affected by the outflow of the Mississippi River.
7. The tests of planktonic species often show the effect of solution of calcium carbonate. The high percentage of such tests at many stations suggests that solution is fairly rapid.
8. Living planktonic specimens occur at many of the deeper stations. They probably represent forms which have fallen to the bottom and survived rather than bottom-living stages.
9. Two hundred and five species and thirteen generic and family groups are used in the analysis of faunal distributions. One new genus *Stetsonia*, and ten new species: *Anomalinoides mexicana, Bolivina lanceolata, Cibicides protuberans, "Discorbis" bulbosa, Globobulimina mississippiensis, Goësella mississippiensis, Reophax irregularis, Stetsonia minuta, Valvulineria mexicana* and *Valvulineria minuta* are described.

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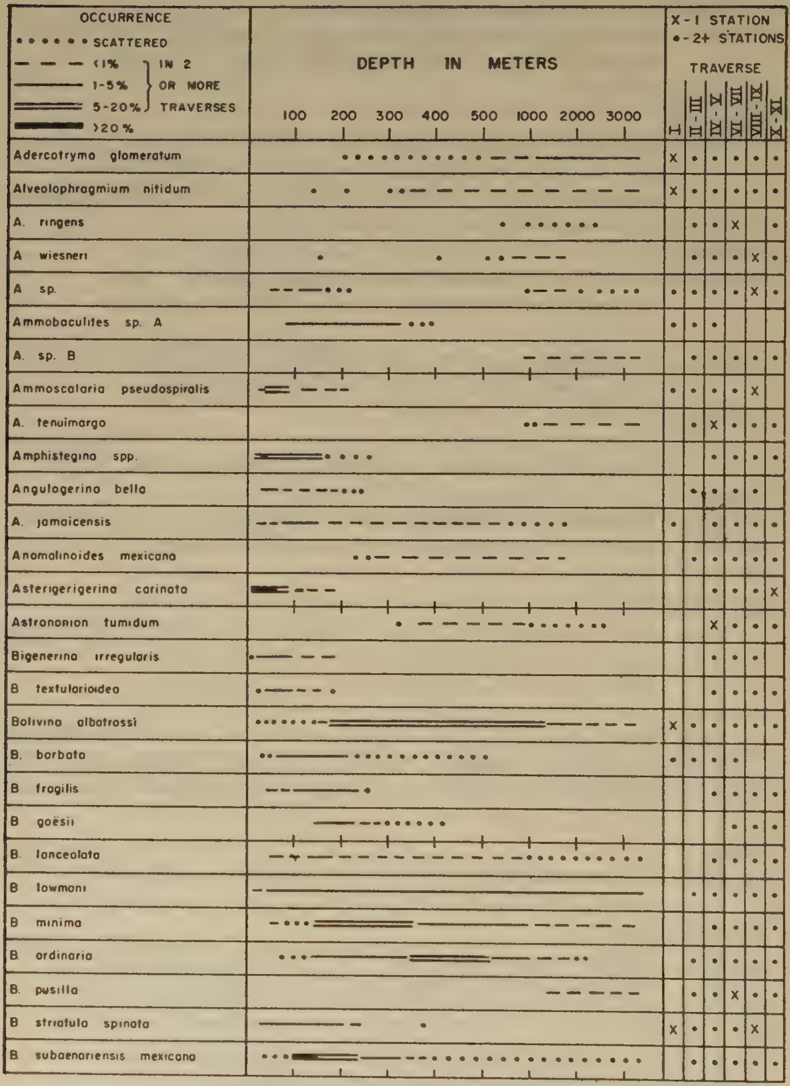

Fig. 3. Generalized distributions of benthonic Foraminifera by depth.

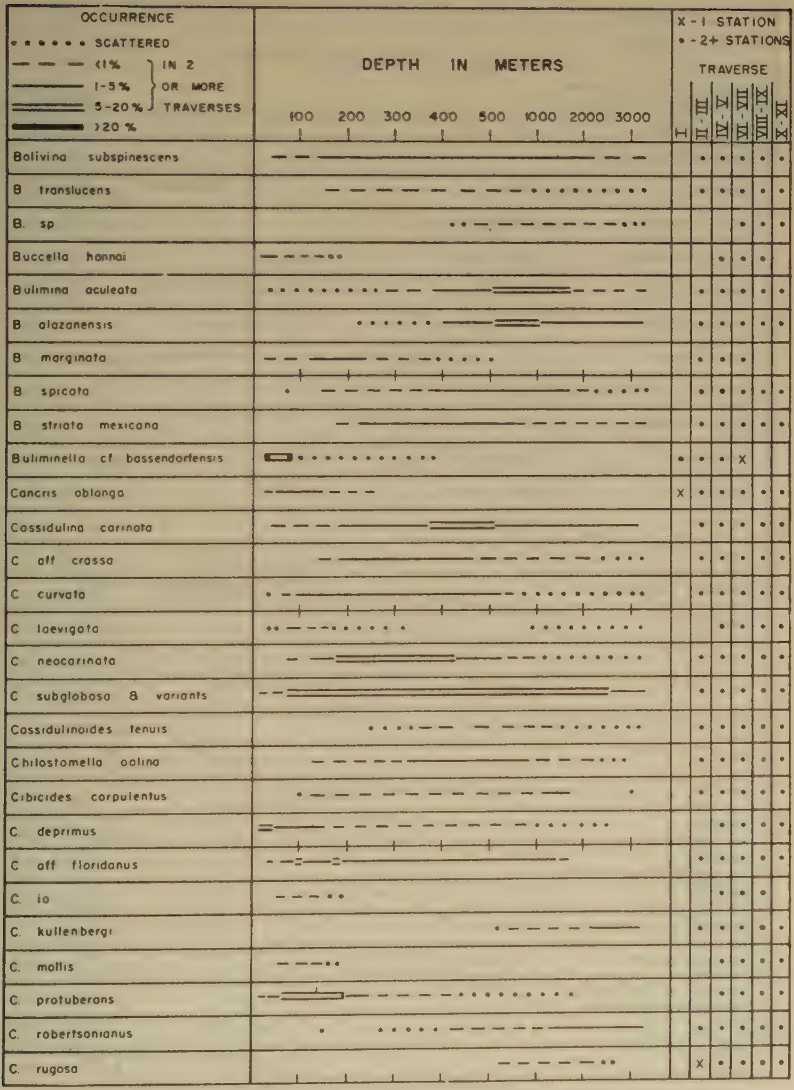

Fig. 4. Generalized distributions of benthonic Foraminifera by depth.

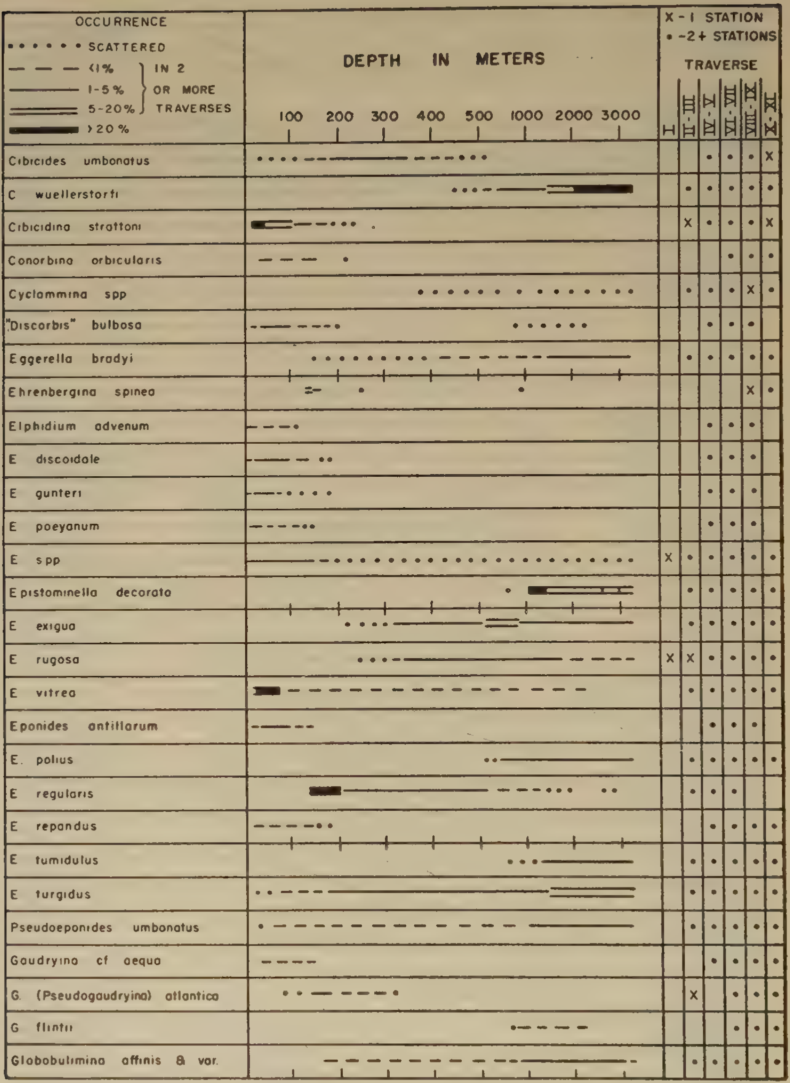

Fig. 5. Generalized distributions of benthonic Foraminifera by depth.

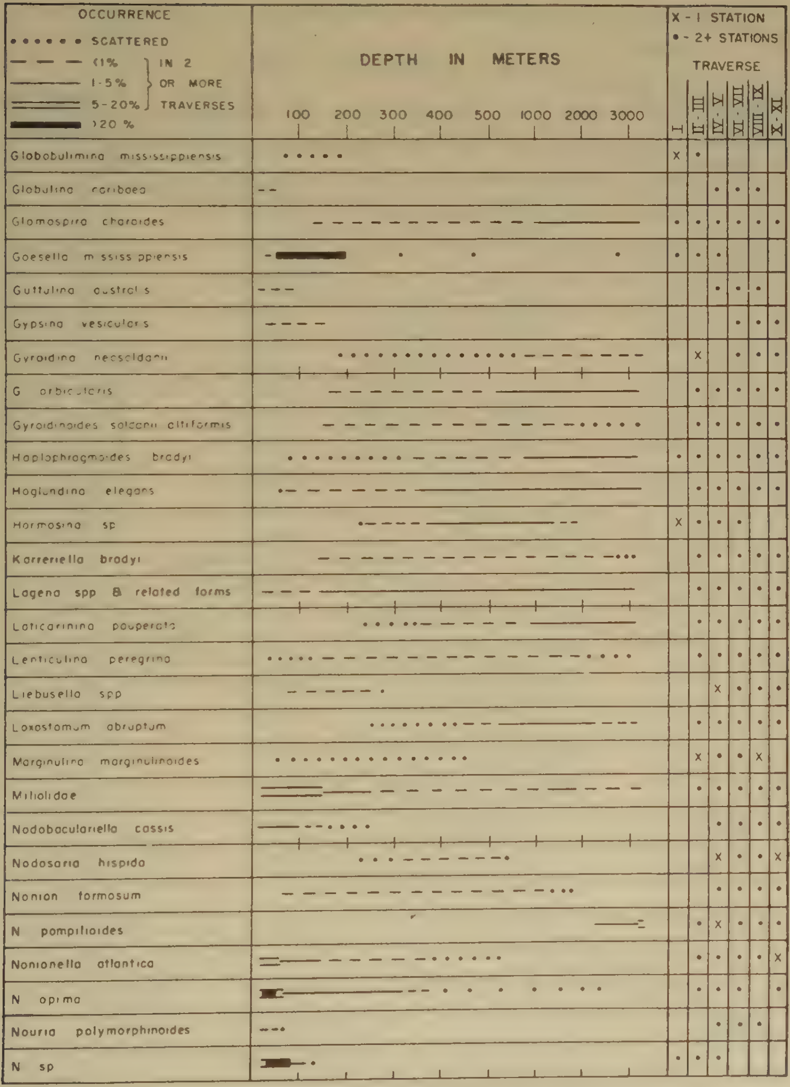

Fig. 6. Generalized distributions of benthonic Foraminifera by depth.

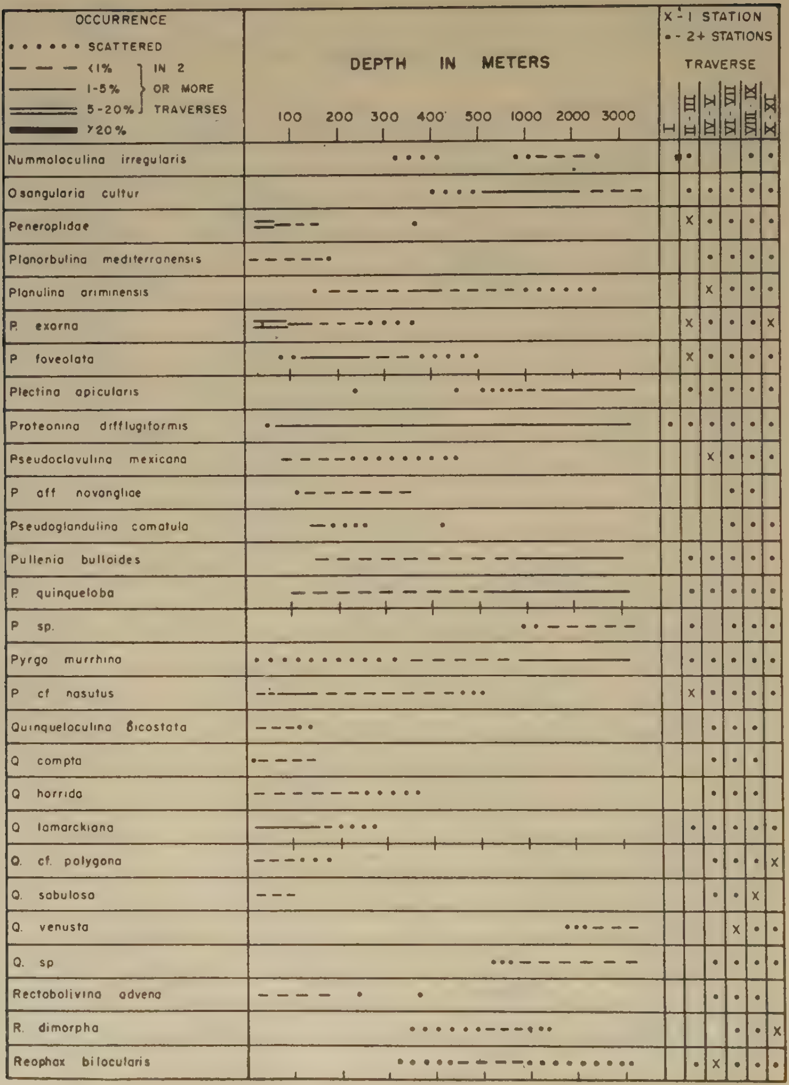

Fig. 7. Generalized distributions of benthonic Foraminifera by depth.

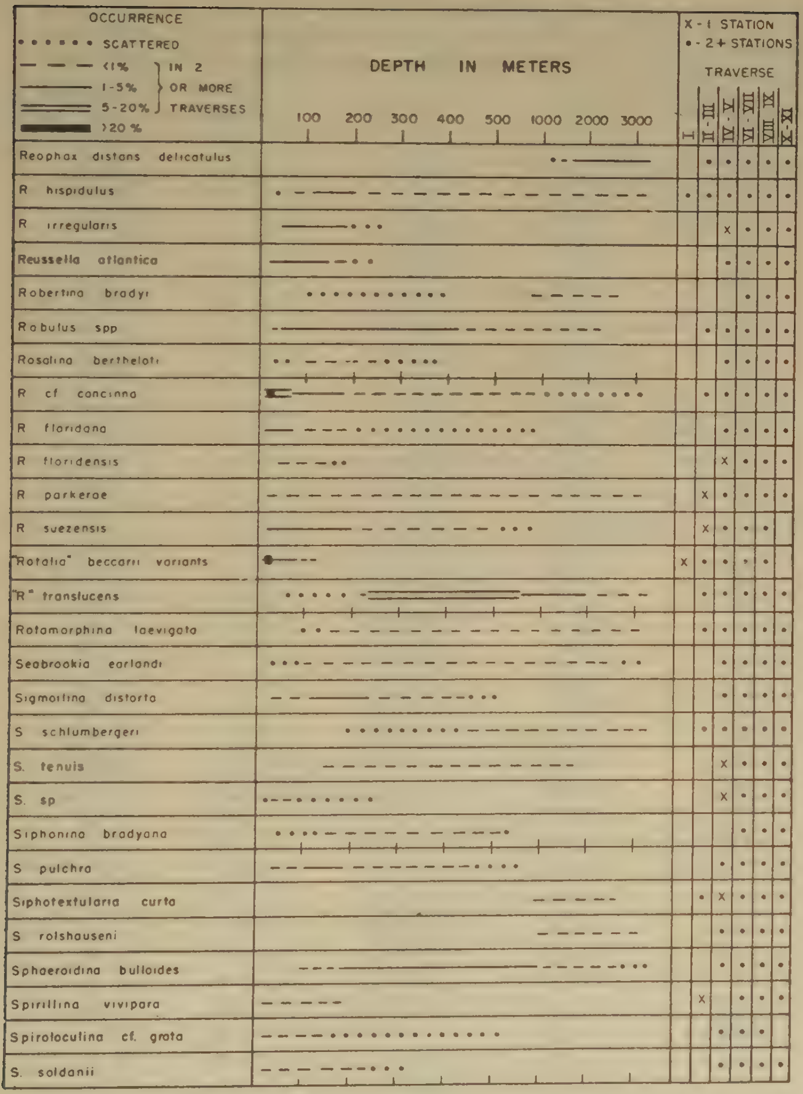

Fig. 8. Generalized distributions of benthonic Foraminifera by depth.

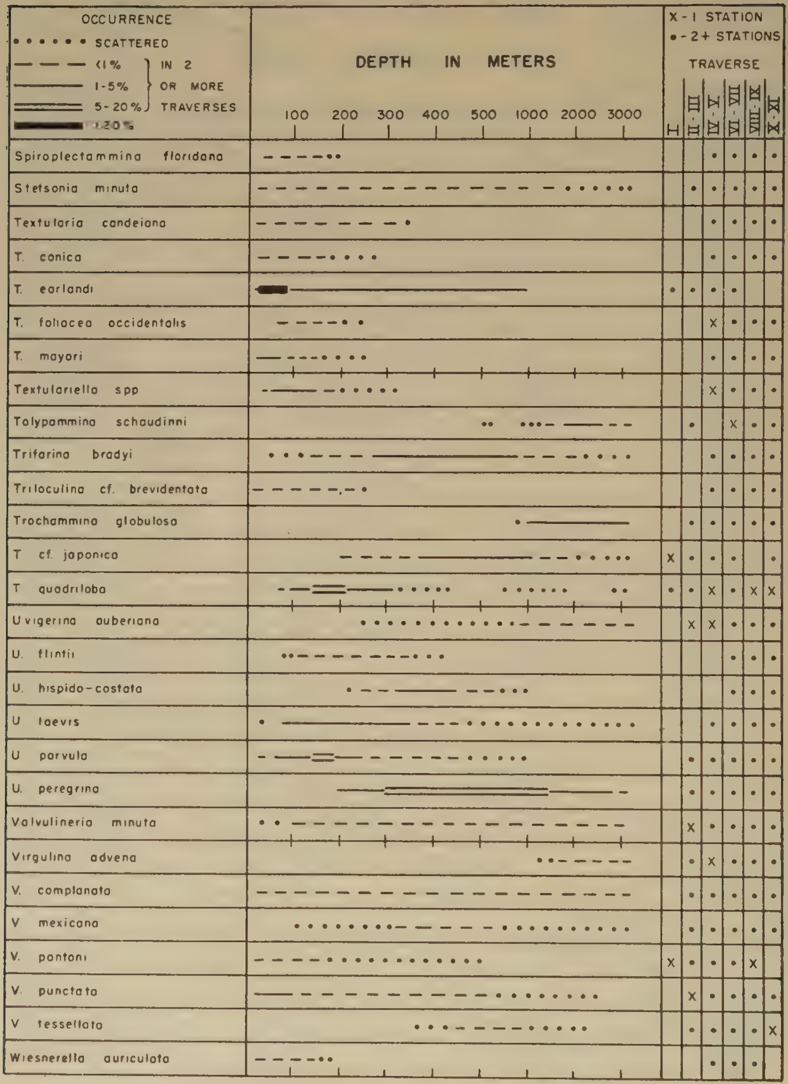

Fig. 9. Generalized distributions of benthonic Foraminifera by depth.

TABLE 3

Locations of stations giving depth and type of sampling gear used. (P — Phleger sampler, O — orange peel dredge, S — Stetson-Iselin sampler, U — underway sampler)

Station	*Sampler*	*N. Latitude*	*W. Longitude*	*Depth in Meters*
1	P	24°51′	85°58′	3237
2	P	24°45.5′	86°27′	3237
3	P	26°01′	88°03′	3017
4	P	26°07′	89°09′	2972
5	P	26°31′	89°09.5′	2788
6	P	26°58.5′	89°12′	2468
7	P	27°26′	89°14′	1875
8	P	27°37.5′	89°14.5′	1417
9	P	27°51′	89°15′	1372
10	P	28°01.5′	89°19′	1298
11	P	28°12′	89°20′	914
12	P	28°18′	89°20′	732
13	P	28°23.5′	89°20′	631
14	P	28°29′	89°22′	471
15	P	28°33.5′	89°22′	298
16	P	28°52′	89°26′	33
17	P	28°49′	89°26′	58
18	P	28°45.5′	89°27′	88
19	P	28°43′	89°26′	106
20	P	28°41′	89°25.5′	113
21	P	28°39′	89°25′	142
22	P	28°37′	89°24.5′	168
23	P	28°35′	89°24′	208
24	P	28°32.5′	89°24′	314
25	P	29°10′	88°56′	22
26	P	29°08.5′	88°55′	53
27	P	29°06′	88°53′	77
28	P	29°04.5′	88°52′	106
29	P	29°04.5′	88°52′	155
30	P	29°01′	88°49.5′	205
31	P	28°56′	88°46′	373
32	P	28°50.5′	88°42.5′	400
33	P	28°44.5′	88°39.5′	1024
34	P	28°39′	88°36′	1262
35	P	28°34′	88°33′	1481
36	P	28°27.5′	88°24.5′	1719

Station	*Sampler*	*N. Latitude*	*W. Longitude*	*Depth in Meters*
37	P	28°10.5′	88°00′	2388
38	P	28°17′	87°03.5′	1573
39	P	28°22′	87°02′	1144
40	P	28°26.5′	87°00′	960
41	P	28°31′	86°58′	860
42	P	28°35′	86°57′	823
43	P	28°44′	86°53.5′	677
44	P	28°54′	86°57′	650
45	P	29°03′	86°55′	631
46	P	29°13.5′	86°52′	555
47	P	29°24′	86°49′	446
48	P	29°34′	86°45′	223
49	P	29°38.5′	86°44′	183
50	P	29°40.5′	86°43′	165
51	P	29°42.5′	86°42.5′	155
52	P	29°44.5′	86°42′	146
53	P	29°46.5′	86°41′	139
54	P	29°48.5′	86°40.5′	128
55	P	29°50.5′	86°40′	119
56	P	29°52′	86°39′	113
57	P	29°54′	86°38.5′	106
58	P	29°56′	86°38′	—
59	P	29°58′	86°37′	91
62	O	30°00′	86°34.5′	64
63	O	30°02′	86°33.5′	55
64	O	30°04′	86°33′	49
65	O	30°06′	86°32′	43
66	O	30°08′	36°31.5′	39
67	O	30°10′	86°31′	24
68	O	30°12′	86°30.5′	27
69	O	30°14′	86°30.5′	29
70	O	30°16′	86°30.5′	24
71	O	30°18′	86°30′	24
72	O	30°20′	86°30′	22
73	O	30°22.5′	86°30′	20
74	P	29°16.5′	88°01′	204
75	P	29°19′	88°01′	146
76	P	29°21.5′	88°01′	99
77	O	29°24′	88°01′	75
78	P	29°26′	88°01′	71
80	O	29°31′	88°01.5′	42

Station	*Sampler*	*N. Latitude*	*W. Longitude*	*Depth in Meters*
81	O	29°38.5′	88°01.5′	44
82	O	29°35.5′	88°01.5′	36
84	O	29°40′	88°02′	36
85	U	29°42.5′	88°02′	36
86	U	29°45′	88°02′	36
87	U	29°47.5′	88°02′	40
88	U	29°50′	88°02′	40
89	U	29°52′	88°02′	36
90	U	29°53.5′	88°02′	35
91	U	29°55.5′	88°02.5′	31
92	O	29°57.5′	88°02.5′	33
93	O	29°59′	88°02.5′	36
95	U	30°01.5′	88°02.5′	36?
96	U	30°03′	88°03′	21
97	U	30°05′	88°03′	20
99	P	29°18′	87°50′	238
100	P	29°14′	87°54.5′	530
101	P	29°09.5′	87°51′	914
102	P	29°05′	87°48′	1097
103	P	28°50′	87°40.5′	1822
104	P	28°42′	87°33′	2213
105	P	28°32′	87°25′	1417
106	P	28°07′	87°05′	2697
107	P	27°29′	86°38′	3017
108	P	26°38′	86°16′	3072
110	P	25°27′	85°32′	3218
111	P	24°50′	85°23′	3251
112	P	25°13′	84°46′	3283
113	P	25°19′	84°40′	2280
116	U	25°43′	84°13′	155
117	U	25°48′	84°06′	139
118	U	25°48′	84°11′	146
120	P	25°30′	84°59′	3246
121	P	25°34′	84°52′	2560
122	P	25°38′	84°49′	1829
123	P	25°39′	84°47′	1326
124	P	25°42′	84°42′	914
126	P	26°03.5′	84°50.5′	1317
127	P	26°21′	85°01.5′	2150
128	P	26°23.5′	84°58′	1737
129	P	26°41′	85°14′	3180

Station	*Sampler*	*N. Latitude*	*W. Longitude*	*Depth in Meters*
130	P	26°45.5′	85°00′	3200
131	P	26°46′	84°58′	1920
133	P	26°46′	85°02.5′	—
134	P	26°49′	84°55′	950
136	P	26°57′	85°02.5′	1051
137	P	27°06′	85°22′	3160
138	S	27°29′	84°41′	183
140	P	27°18′	84°50′	256
141	P	27°17.5′	84°54.5′	320
142	P	27°17′	84°59′	421
144	P	27°17′	85°15′	914
145	P	27°16.5′	85°29′	2268
146	P	27°31′	85°40′	3164
148	P	27°47.5′	85°45′	1730
149	P	27°51′	85°44′	914
150	P	27°56′	85°32′	585
151	P	28°01.5′	85°22′	366
152	P	28°09′	85°07′	183
153	P	28°11.5′	85°02′	146
154	P	28°14′	84°57′	117
155	S	28°16.5′	84°52′	79
156	S	28°19′	84°46.5′	58
157	S	28°22′	84°41′	62
158	S	28°24.5′	84°36′	60
159	S	28°27′	84°31′	51
160	S	28°30′	84°25.5′	46
161	S	28°32′	84°20′	35
163	S	28°38′	84°08′	36
164	S	28°41′	84°02′	31
165	S	28°43.5′	83°56′	31
166	S	28°46′	83°50′	29
167	S	28°49′	83°44′	26
168	S	28°51.5′	83°39.5′	22
169	S	28°54′	83°34.5′	20
170	S	28°55′	83°28.5′	20
171	S	28°56.5′	83°22′	15
172	S	28°58′	83°16.5′	12?
174	S	29°28′	85°29′	22
175	S	29°24′	85°32′	31
176	S	29°20′	85°35.5′	46
177	S	29°16′	85°39′	49
178	S	29°12′	85°42′	86

Station	*Sampler*	*N. Latitude*	*W. Longitude*	*Depth in Meters*
179	P	29°08.5′	85°45′	146
180	S	29°04′	85°49′	183
181	P	28°59′	85°52′	186
182	P	28°54.5′	85°56′	237
183	P	28°49′	85°59′	274
184	P	28°45′	86°02.5′	274
185	P	28°38′	86°07′	320
186	P	28°31.5′	86°10′	347
187	P	28°24.5′	86°13′	457
188	P	28°18.5′	86°15.5′	585
189	P	28°13′	86°18′	732
190	P	28°06.5′	86°21′	878
191	P	27°48′	86°30′	2999
196	P	29°26.5′	86°59′	713
197	P	29°26.5′	86°57.5′	549
198	P	29°26.5′	86°57′	549
199	P	29°27′	86°58′	735
200	P	29°27.5′	86°58′	600
201	P	28°37′	89°49′	430
202	P	28°40.5′	89°45′	128
203	P	28°40′	89°45.5′	201
204	P	28°42.5′	89°42′	91
205	P	28°44′	89°40′	82
206	P	28°45.5′	89°38.5′	79
207	P	28°46.5′	89°36.5′	82
208	P	28°48′	89°34.5′	73
209	P	28°49′	89°33′	86?
210	P	28°50.5′	89°31′	86?
211	P	28°51.5′	89°29.5′	51
212	P	29°11′	88°52′	62
213	P	29°16′	88°48′	55
214	P	29°21′	88°44′	49
215	P	29°25.5′	88°40′	47
216	P	29°30′	88°36′	42
217	P	29°35.5′	88°32′	40
218	P	29°40′	88°28.5′	42
219	P	29°45′	88°24.5′	38
220	P	29°49′	88°21′	37
221	P	29°53′	88°17.5′	35
222	P	29°57.5′	88°14.5′	33
223	P	30°01.5′	88°11′	33
224	P	30°05.5′	88°07.5′	20
225	P	30°08′	88°05.5′	20

TRAVERSE	I											II																					
STATION	211	210	209	208	207	206	205	204	202	203	201	16	17	18	19	20	21	22	23	15	24	14	13	12	11	10	9	8	7	6	5	4	3
DEPTH IN METERS	51	?86	?86	73	82	79	82	91	128	201	430	33	58	88	106	113	142	168	208	298	314	471	631	732	914	1298	1372	1417	1875	2468	2788	2972	3017
TOTAL PLANKTONIC POPULATION	0	0	0	0	0	0	0	9	0	0	0	0	0	3	0	0	0	21	0	300	17	2	7	75	0	2 000	5 000	7 000	100 000	50 000	10 000	30 000	60 000
TOTAL BENTHONIC POPULATION	44	1200	225	650	175	125	250	175	175	150	125	31	450	250	275	175	125	650	100	800	550	36	250	425	175	325	375	425	175	550	700	500	1200
Adercotryma glomeratum										.7									2				.4			1	1	5		1		3	2
Alveolophragmium nitidum									.5											.5		3	.4		1	.3	.8	2					
A ringens																										.9	.3	.9					
A. scitulum									2		4							.3	2	.2	.4	6			1			.5			.6	.4	
A subglobosum																				.2								2		.4		1	
A. wiesneri																							1	.5	5	3	2						
A sp.			.5	1	14	9	5	9	7	3					1	1	3										.8	2					
Ammobaculites sp A						3		2	3	8					.4	3	2	.8	3		1												
A sp. B																									.6	.9	1					.8	
Ammodiscus spp						.7		.6	1	5							4				1	3	.4	.7	3	.9	.3			.4	.6		1
Ammoscalaria pseudospiralis			1	8	18	9	5	3	.5					.4			8	.3	.9														
A tenuimargo																										.3	.3	5	1	2		2	.3
Angulogerina jamaicensis									1		2																						
Anomalinoides mexicana																											.3						
Bolivina albatrossi																		.5		9	8		3	6	3	8	.8	3	4				
B barbata		.2		7														13		1													
B lowmani														.4						.7				1		2	1	.2			2	.4	4
B ordinaria																		3		3	4		11	7									
B. paula																																.4	1
B pulchella primitiva																														.4	.6	.4	2
B pusilla																											.8		1		.6	.8	
B striatula spinata				4																													
B subaenariensis mexicana																				.7								.2		.4			
B subspinescens																				1			.4	1			.5			.4	1	1	1
B translucens																							.8	.2									
Bulimina aculeata																							14	2	4	11	13	2	7		.6		
B. alazanensis																										5	1	2		.7		.4	.7
B. marginata																		33		13	1												
B spicata																		.2		1	.2		4	.7		4	1	2	2				
B striata mexicana																		3		12	2		13	5		.6		.9	.6	1	.6		.3
Buliminella cf. bassendorfensis				30								3																					.7
Cancris oblonga				.3																													
Cassidulina aff. crassa																												.2				.4	
C. curvata																				2			.4										
C neocarinata																				.5			.8	.2									.3
C subglobosa & variants																				.7				.2		2	4	4	11	6	4	3	2
Cassidulinoides tenuis																														.4			.3
Chilostomella oolina																					1		2	.7		.9					.6	.4	
Cibicides corpulentus																											.3						.3
C aff. floridanus																				4			4	3	.6	4	3	4					
C. kullenbergi																											.3					.4	
C robertsonianus																										2	.8	.2	5	4	3	6	.7
C rugosa																										.3							
C wuellerstorfi																										.9	.8	2	3	18	3	20	13
Cyclammina spp																						3	.8	.2	.6		1	.7					
Dentalina - Nodosaria																				.7	.2									.4	.6		
Eggerella bradyi																								.5		.9	.5	.5		1		1	.3
Elphidium spp									2							.6				.7													
Epistominella decorata																										.3	3	2	18	4	20	8	21
E. exigua																							7	4		4	1	.5	3	.4	2		1
E. rugosa																																	.3
E. vitrea														.4																			
Eponides polius																				.5							.3			3	8	4	6
E regularis																		12		2	3		2								.6		
E tumidulus																											.3		2	.4	3	6	3
E. turgidus																							4	.5		.6	6	.9	.6	4	12	4	6
Pseudoeponides umbonatus																										.3	.5		.6	3	1	.4	1
Gaudryina (Pseudogaud.) atlantica																				.2													
G cf. minuta																			.9	.2	1	8	1	3	5	.3	.3						
Globobulimina affinis & variant																		.8		.2			.4	2	.6	3			2	5	1		
G. mississippiensis				.3														.2															
Glomospira charoides									.5	3	4									.2	.7		.4	.7	2	6	6	1				1	
G cf. gordialis											3						.9	.3	3		.5	6		.5						.4			
Goësella mississippiensis		.6	21	24	22	31	43	30	44	20				3	92	86	53	1	15		.5	3									.6		

Table 4. Percentage distribution of benthonic Foraminifera in traverses I and II (pt.).

TRAVERSE	I											II																					
STATION	211	210	209	208	207	206	205	204	202	203	201	16	17	18	19	20	21	22	23	15	24	14	13	12	11	10	9	8	7	6	5	4	3
DEPTH IN METERS	51	?86	?86	73	82	79	82	91	128	201	430	33	58	88	106	113	142	168	208	298	314	471	631	732	914	1298	1372	1417	1875	2468	2788	2972	3017
Gyroidina orbicularis																				.2				.7		2	2	4	5	3	1		
Gyroidinoides soldanii altiformis																										.3							
Haplophragmoides bradyi						.7				2								.3	4	.2	3		.4	3	7	1	.5	.9	3	3		2	2
Hoglundina elegans																													6	4	.6	2	3
Hormosina sp											11									.7	1		2	2	4	.6	3	4					
Karreriella bradyi																										.9							
Lagena spp & related forms																		.2		1			.4	1			3	.5	2	6	9	2	5
Laticarinina pauperata																										.9	1	.9	1	3	.6		.3
Lenticulina peregrina																										.3		.2	.6				.3
Liebusella spp																																.8	
Loxostomum abruptum																												.2					
Marginulina marginulinoides																				.7													
Miliolidae																										.3	.3			.4	.6	.4	.3
Nonion pompilioides																														2	.6	2	1
Nonionella atlantica																							.4						.6				.7
N. opima	9				1															.2	2												
Nouria sp	59	16	16	6	10	4	7	2	.5			81	18	30	3						.2												
Nummoloculina irregularis																										.3							
Osangularia cultur																							.4	5	.6	2	.8	3	2			.4	
Planulina exorna																			.9														
P. foveolata																				.2													
Plectina apicularis																									.6	.3	1	2	.6	.7		3	1
Proteonina atlantica																				.2									1	1	2		
P. difflugiformis			.9	7	18	25	20	24	9	13	5			2	2	6	3	3	8	1	3	3	.8	2	3	.6	6	3			.6	3	
Pullenia bulloides																				.7	.2		.4			2	1	.7	1	2	1	.8	.3
P. quinqueloba																									.6	2			.6	.4	.6	.8	.3
P. sp																												.2	.6	3	2	.8	
Pyrgo murrhina																											.5						.3
P. cf. nasutus																										.3							
Quinqueloculina lamarckiana																			.9										.6				
Q. sp																										.6	.3				.6		.7
Reophax bilocularis																										.3	2	.2				.4	
R. distans delicatulus																												4	.6	1	.6	6	1
R. guttifera																		.2	.9	1		3		2	2								
R. hispidulus			9		3			2	3	1				.4		.6	2	.3	2		7		.8	2		.6		.2		.4			.3
R. scorpiurus					3	2	5	4	3								2	.3	10	1	3											.4	
R. sp																			9		.7	3		1									
Robulus spp																		.9		3						.3		.7	.6				
Rosalina cf. concinna																		.2									.3						
R. parkeroe																																	1
"Rotalia" beccarii variants		3					.4					16	2																				
"R" translucens																				.2						.3	.3		.6			.8	.3
Rotamorphina laevigata																							.4	.2							.6		
Saccamminidae & related forms									2	.7	.9						7	5	2	.7	.9	3	8	3	18	3	2						
Sigmoilina schlumbergeri																										.9	.3	.9		.4			1
Siphonina pulchra																																	.3
Siphotextularia rolshauseni																											.5	.2				1	1
Sphaeroidina bulloides																		3		8	9		8	8	1		.8	5	.6				
S. compacta																										.3							
Stetsonia minuta																										.3	4					.4	
Textularia earlandi	30	77	48	5			.4			15	35		79	6.1			.9				.9	11	2	9	3								
Tolypammina schaudinni																			.9						4	.6	1	1	.6			.4	
Triloculina tricarinata																													.6		1	.4	.7
Trochammina advena									1	2	6								1		4												
T. globulosa																										.9	2	2	1	2		.4	.7
T. cf. japonica											7								4	1	8	13	3	5	4	1	2	1					
T. quadriloba				1	11	12	12	22	9	20	12				1	2	4	6	17	.5	5		.4		6								
T. squamata & related spp.	2																																
T. cf. tasmanica			3			3	2		2	5							3	3	5	2	18			.2	2	1	.5	.9					
Uvigerina auberiana																																.4	
U. peregrina																		.6		16	5		6	12	1	6	6	15	5	4		1	
Valvulineria mexicana																		.8		4			2	.2				.7		2	2	.4	.7
V. minuta																				.2							.3	.2					
Virgulina advena																															.6	.4	
V. complanata																											.8			.4	.6	.4	1
V. mexicana																							.4								.6		.7
V. pontoni				2														.5			1												
V. tessellata													.2										1	2		3							
Wiesnerella auriculata											.9																						
Miscellaneous spp		3	9	3				1	9	2	9		.8	2	.6	.8	7	5	8	3	4	32	2	4	11	4	5	9	5	5	9	4	8

Table 5. Percentage distribution of benthonic Foraminifera in traverses I and II (pt.).

TRAVERSE	III													IV												
STATION	25	26	27	28	29	30	31	32	33	34	35	36	37	225	224	222	221	220	219	218	217	216	215	214	213	212
DEPTH IN METERS	22	53	77	106	155	205	373	400	1024	1262	1481	1719	2388	20	20	33	35	37	38	42	40	42	47	49	55	62
TOTAL PLANKTONIC POPULATION	0	1	29	11	21	10	69	300	425	1400	700	1400	7800	4	175	550	800	850	725	1000	0	250	200	100	0	5
TOTAL BENTHONIC POPULATION	125	650	1200	700	1300	900	750	700	700	450	300	325	325	1200	10800	30700	27500	9700	19100	27200	150	14900	9900	4300	92	350
Adercotryma glomeratum								.1		.2	.7	2														
Alveolophragmium nitidum						.1				2	1															
A. ringens												.6														
A. scitulum						.1	.4	.1					.6													
A. subglobosum							.3					.6														
A. wiesneri					.3			.4	2	3	6	.9														
A. sp.										.9	2	2													1	.3
Ammobaculites sp. A						.9	.4																			
A. sp. B												.3														
Ammodiscus spp.						.1		.3	.9	.2	1	1	.3													
Ammoscalaria pseudospiralis				.3		.2								2	1	.2	1	.4	.7	.8	30	.3	4	2	22	.9
Amphistegina spp.																.1		.1	.2			.2				
Angulogerina bella				.1											.1	.4	.9	1	2	2		2	6	4		
A. jamaicensis															.3				.2					.2		
Anomalinoides mexicana											.3															
Asterigerina carinata														2	1	2	2	.7	.5	.6		.4	.7			
Bigenerina irregularis														5	2	2	3	3	5	3		2	4	2		
Bolivina albatrossi						.2	.8	10	5	8	2	1														
B. barbata			.2	15	26	14			.6																	
B. lowmani				.3			3	.6	1	.9	3	2	2	.3	.3		.7	.4	.3	.5		.4		1		1
B minima																									1	
B ordinaria						19	16	6	.6	.5	.3	.9														
B pulchella primitiva															.8	.8	.9	.5	.7	1		.6	1	1		
B pusilla												.6	.6													
B. striatula spinata		.3	5	3		2											.2		.2	.2		.3	1	2		
B. subaenariensis mexicana				21	32	1	1				.3													.2		
B. subspinescens							.3	.4			.3	2	1									.1	.3			
B translucens							2			.5																
Buccella hannai														2	1	1	1	.7	1	.5		.7	.3	.8		
Bulimina aculeata				.3			.8	10	16	10	16	7	.3													
B. alazanensis								6	3	4	.7	.3														
B marginata				.3	14	13	.5								.1					.8		1	1	1		
B spicata						.1	.5	3	3	.2	2	1														
B. striata mexicana							4	8				.9														
Buliminella cf. bassendorfensis	6	27	35	7	.6		.3					1			.6	.2	.2	.1	.5	1	.6	4	5	5		
Cancris oblonga																.2	.2	.5	.5	.8		.3	1	.8		
Cassidulina carinata							13	17	.3	.5																
C. aff. crassa					.3																					
C. subglobosa & variants								.6		2	.3		.6	.1	.2	.6	2	.9	2	3	.6	2	1	2		
Chilostomella oolina								1	1	2		1														
Cibicides corpulentus										.2		.3														
C deprimus														1	5	6	5	4	2	2		2	.2	1		
C. aff. floridanus							1	1		1	.7	.9														
C. kullenbergi													.3													
C. protuberans														.1				.1		.1						
C robertsonianus										.5	.3	.9	6													
C. wuellerstorfi										.5	.7	2	.9													
Cibicidina strattoni					.2									20	9	15	15	17	16	16	2	9	12	5		
Cyclammina spp							.1	.4		.2		.9														
Dentalina - Nodosaria							.2											.1			.6	.1		.2		
"Discorbis" bulbosa															.1	.9	.6	1	1	2		1	.2			

Table 6. Percentage distribution of benthonic Foraminifera in traverses III and IV (pt.).

TRAVERSE	III													IV												
STATION	25	26	27	28	29	30	31	32	33	34	35	36	37	225	224	222	221	220	219	218	217	216	215	214	213	212
DEPTH IN METERS	22	53	77	106	155	205	373	400	1024	1262	1481	1719	2388	20	20	33	35	37	38	42	40	42	47	49	55	62
Eggerella bradyi									.3	.5	.3	1	2													
Elphidium advenum														.3	.1											
E. discoidale														2	.4	.7	2	2	5	2		2	.7	.4		
E. gunteri			.2											9	1	3	.8	1	1		1	2	4	1		
E. poeyanum														.3	.8	.3	.9	.2	.6	.6		.1	.8	.4		
E. spp.														5	4	4	3	3	3	3	1	2	2	2		
Epistominella decorata												1	14													
E. exigua					.3			3	2	2	1	.6														
E. rugosa										1																
E. vitrea		34	29	17	4					1				.2	.7	.1	.4	.7	2	3		8	5	14		
Eponides antillarum														.1		.2	.6	.7	.3	.1						
E. polius												.3														
E. regularis					.6	21	6	.6	5	.2																
E. tumidulus											.7	.3														
E. turgidus										1	1	5	22				.1									
Pseudoeponides umbonatus								.3				.3	.6													
Gaudryina cf. minuta							.1			.2				.3	.4	.1								.2		
Globobulimina affinis & variant							.5	.6	3	6	3	.6	2													
G. mississippiensis				2	3	3																				
Globulina caribaea														.2	.1		.1		.2							
Glomospira charoides						.2			3	.7	8	4	1													
G. cf. gordialis						.2		.1					.3													
Goësella mississippiensis			2	9	1	6																		.2	22	12
Guttulina australis														2	1	.1	.3	.1	.2	.1	.6	.2	.7			
Gyroidina neosoldanii												.3														
G. orbicularis								.6	3	.9	2	5	2													
Gyroidinoides soldanii altiformis								.1																		
Haplophragmoides bradyi						.2		.6	.3		4	1	5													
Hormosina sp.						.1	.1	1	1	5	3	1														
Karreriella bradyi										.2	.3															
Lagena spp. & related forms			.2	.1	.2	.1	1	.1	2	.9	.7	1	2		.1		.1			.5		.2	.5	.6		
Laticarinina pauperata											.7	.3	.9													
Lenticulina peregrina						.4	.4	.1		.2	.3															
Loxostomum abruptum										.2	.3															
Miliolidae										.2				6	2	1	4	4	.7	.8		2				
Nodobaculariella cassis														.2	.3	.8	.2					.2				
Nonion pompilioides													.3													
Nonionella atlantica					.7	.2	.5							2	3	10	5	6	7	7	.6	6	10	9		
N. opima	2	31	19	7	5	1	1		.6	2			1	2	9	1	1	2	5	7	2	11	15	20		
Nouria polymorphinoides														.3	.3				.2		9					
N. sp	11	2	4	3																					22	5
Nummoloculina irregularis											.3															
Osangularia cultur								2	4	4	2	3	.6													
Peneroplidae							.1							1		.7	.2	.7	.2							
Planorbulina mediterranensis																			.2							
Planulina exorna														1	.1	4	4	7	6	3		2	1	1		
Plectina apicularis											.3	2	4													
Proteonina atlantica															.3	1	1	.7	1	1	48	.8	3	1	20	.3
P. difflugiformis			.2	.1		.8	3	2	2	4	5	9	.3													
Pullenia bulloides							.7	.6	.9	.5	.3		.9													
P. quinqueloba								.1	1	.9	.7	.9	.6													
P. sp.													.3													
Pyrgo murrhina															.3											
P. cf. nasutus																.1	.4			.5		.8		.2		
Quinqueloculina bicostata														.1	.2	.1	.1		.2	.1		.1		.2		
Q. compta														2	.4	1	1	2	2	.5		1		.6		
Q. horrida																	.4		.3	.6			.2	.2		

Table 7. Percentage distribution of benthonic Foraminifera in traverses III and IV (pt.).

TRAVERSE	III													IV												
STATION	25	26	27	28	29	30	31	32	33	34	35	36	37	225	224	222	221	220	219	218	217	216	215	214	213	212
DEPTH IN METERS	22	53	77	106	155	205	373	400	1024	1262	1481	1719	2388	20	20	33	35	37	38	42	40	42	47	49	55	62
Quinqueloculina lamarckiana														1	.4	1	1	1	3	1		1		.4		
Q. cf. polygona																						.1				
Q. sabulosa														.3	.2	.5	.1	.5	.3							
Q. sp.										.2																
Rectobolivina advena																.2	.4	.5	.3	.8		.7	1	1		
Reophax bilocularis											.3															
R. distans delicatulus												5	12													
R. guttifera										.2																
R. hispidulus				.4	.3	.1		1	.3	2	1	.9	2													
R. scorpiurus						.8	.4	.1									.1									
R. sp.						.4			.3																	
Reussella atlantica															.7	1	.8	4	2	1		1	2	2		
Robulus spp.			.2	.8	.2	.1	.3	.3			.3					.1	.1	.5	1	.7	1	.8	.7	.6		
Rosalina bertheloti																	.2	.1								
R cf. concinna					.2									11	21	24	23	18	11	16	.6	18	1	.2		
R. floridana														6	5	4	3	2	2	2		1	2	1		
R. parkerae																	.2		.2	.4			.2	.4		
R. suezensis													.3			.4	1	1	2	2		1	.3			
"Rotalia" beccarii variants	.2	.6	.3											14	20	4	3	3	2	2	.6	3	5	3		
"R." translucens							3	3		.7	.7	.6														.9
Rotamorphina laevigata								.1		.7	.3		.3													
Saccamminidae & related forms						.2	.3	.1			1	1														
Seabrookia earlandi																	.1									
Sigmoilina distorta																	.2		.5	1		.4	.7			
S. schlumbergeri											.3	.3														
S. tenuis													.3													
Siphonina pulchra																			.2				.2			
Siphotextularia curta										.2	.3	.3														
Sphaeroidina bulloides						.3	1	3	4	.5																
Spirillina vivipara											.3															
Spiroloculina cf. grata															.8	.8	.5	.4								
Stetsonia minuta										.2	.3				.3	.5	.8	.7	.8	2			1	2		
Textularia candeiana																.1	.1									
T. earlandi	21	5	.3	3	.6	5	.8	2	2																12	79
T. mayori															.2	.9	2	2	1	1		.6				
Tolypammina schaudinni											.3	.9	.3													
Triloculina cf. brevidentata														.1	1	.7	.4	.4		.4		.2		.4		
T. tricarinata								.1		.7																
Trochammina advena						.4	.1																			
T globulosa									.6	1	5	4	3													
T. cf. japonica							.8	1	1	.5	.7	3														
T. quadriloba						.8	.4		.9			.3														
T. squamata & related spp.				.4										.2	.2			.1		.1						
T. cf. tasmanica						.1	.1				2	1	.3													
Uvigerina laevis																.1										
U. parvula			2	9	7												.2		.5	.9		1	1	3		
U. peregrina						2	12	7	16	7	5	.3	1	.1												
Valvulineria mexicana							11	.7																		
V. minuta																						.1				
Virgulina advena													1													
V. complanata							.1					.9	.6		.2		.2	.2	.5	.1		.2	.2			
V. mexicana							.5	3																		
V. pontoni		.2	1	1	.3	.1										.1	.2	.1	.3	.9		2	2	4		
V. punctata			.2												.8	1	2	2	.5	1		.2		.4		
V. tessellata							.1	.6	13	15	5	.9														
Wiesnerella auriculata												.9			.1							.2				
Miscellaneous spp.	59		1		3	6	11	1	.4	2	6	12	6	2	3	3	2	3	4	3	2	2	1	2		.6

Table 8. Percentage distribution of benthonic Foraminifera in traverses III and IV (pt.).

TRAVERSE	V																																
STATION	97	96	95	93	92	91	90	89	88	87	86	85	84	81	82	80	78	77	76	75	74	99	100	101	102	103	104	105	197	198	200	196	199
DEPTH IN METERS	20	21	?36	36	33	31	35	36	40	40	36	36	36	44	36	42	71	75	99	146	204	238	530	914	1 097	1 822	2 213	1 417	549	549	600	713	735
TOTAL PLANKTONIC POPULATION	64	24	10	600	475	80	24	96	400	275	44	52	150	4	650	125	5 000	1 600	5 800	950	650	900	1 400	2 800	900	3 600	1 900	22 400	4 600	4 800	34 900	17 500	35 300
TOTAL BENTHONIC POPULATION	5 600	4 900	2 100	15 100	22 400	7 300	2 300	3 000	8 000	7 400	1 900	2 200	4 000	1 100	7 000	1 400	22 000	4 400	12 800	5 000	3 100	3 200	2 900	1 300	550	650	650	1 900	1 100	2 500	3 200	4 100	5 800
Adercotryma glomeratum																									1	1	.3		.5	.5		.2	
Alveolophragmium nitidum																							.1		.7	1	.3			.3			
A ringens																										.3		.4					
A scitulum																											.3						
A subglobosum																							.1		.7			.4		.3			
A wiesneri																									.7	6		.4	.2	.2			
A sp																									1	.6							
Ammobaculites sp. A																			.2	.2													
A sp B																										.3	1						
Ammodiscus spp																									2	.3	.3		.7				
Ammoscalaria pseudospiralis	.3	.3	.3	.3		.4		.1			.6	.5	1																				
A tenuimargo																										.3							
Amphistegina spp				.1		.8	3	2	.8	.6	3	1	.8				.3	5				.1											
Angulogerina bella		.2	.3	.1	.6	.2		.1	.8	.2	.2	.7	.2		.5		.9	.4	.8	.8	.5	.4											
A jamaicensis								.1		.4	.2	.2			.5		1	1	2	4	.8	2	.3	.6	.4								
Anomalinoides mexicana																							.3	1		.6	.3	.4	.5	.3	.2		.7
Asterigerina carinata	2	5	.4	2	2	2	3	1	1	2	.6	1	3	2	.7	.6	2	2	.8														
Astrononion tumidum																												.4	.4				
Bigenerina irregularis	1	1		1	2	3	1	2	5	2	2	3	3	4	4	3	5	1	2														
B. textularioidea							.7		.2		.9	1	1	2	.9	5	.3	1	.5														
Bolivina albatrossi																				.2	1	3	2	7	3	.3		4	3	3	6	9	9
B barbata																				2	1	.4	.1										
B. fragilis										.2							.3		1	7	3	2	.3										
B lanceolata																			.5	.8	2	1	.4	.3									.3
B lowmani				.2	.1	.4	.3		.2	.4	.2	.2					1		.2	4	3	3	7	2	3	3	4		1	3	2		1
B minima																				.5	6	4	8	.9						.2	1	.6	2
B ordinaria																							2	4	1	.3			7	9	8	1	6
B paula																							.1	.3									
B pulchella primitiva	.8	.5		.2	.1	.4		.1		.2	.2	.2							.2	.3	.6	.8	.1	.3									
B pusilla																	.3			.3						2	2						
B striatula spinata															.2			.7	1	.6	.5	.1		.3									
B subaenariensis mexicana																			1	4	8	10	1	.6							.8		.6
B subspinescens						.2										.3	.6	1	.5	2	3	4	3	.9		.9	.9		3	2	1		.4
B translucens																				.2	.3	.1	.7	.3	.7								
B. sp																														.5			.8
Buccella hannai	1	2	2	.4	1	1		1	.4	3		.4	1		1		.6		.5	.2													
Bulimina aculeata																							3	10	8	2	3	10	4	1	6	3	4
B alazanensis																							1	9	4	.9		4	7	5	1	12	9
B marginata																		.4	.8	3	2	1	.6										.4
B spicata																	.3			1	1	1	.8	2	2	2	1	1	.2	.2		.4	.4
B striata mexicana																					.9	.5	2	2	.4		1	.8	2	2	3	5	5
Buliminella cf. bassendorfensis				.1		.2					.2																						
Cancris oblonga	.3			.6	.1	.2			.6	.2	1	.4	.2		1	.9	1	2	2	1	.6	.1											
Cassidulina carinata																							6	1	.4			.4	.9	2	.5	.2	7
C. aff crassa																						.3		.6						.3	.2	.2	.3
C. curvata												.2					.6	.4	.8	1	2	3	.4						.2	.2	.8	1	
C. laevigata																	1	.7	2			.1											
C. neocarinata																			.5	3	2	3	4	1				.4	2	1	5	6	1
C. subglobosa & variants				.2	1	.2		1	.4	2	6	1	.2	.4	2	.6	4	3	8	17	23	16	11	2	.7	.9	4	8	9	8	4	3	2
Cassidulinoides tenuis																													.5	.3	.2		.1
Chilostomella oolina																				.6	1	.8	1	2	.7		.3		2	1	1	.2	.6
Cibicides corpulentus																			.2	.2					.4				.2	.3	.5		
C. deprimus	12	6	9	5	5	3	.7	2	.8	.9	.2	.2	.8	.4	.7		1	2	2	.5	.4	.6		.3									
C. aff. floridanus																	2	4	6	5	2	.6	.6	3	1	.6		.4	3	4	5	4	1
C. io																	.3	1	1	.2													
C. kullenbergi																										.3							
C. mollis																	.9		1	.3													
C. protuberans								.4	.2		.2	.4	.4	.4	.2	1	5	10	2														
C. robertsonianus																								.3	.4	2	1	3		.2			
C. rugosa																								.6	.4				.2				

Table 9. Percentage distribution of benthonic Foraminifera in traverse V (pt.).

TRAVERSE	V																																
STATION	97	96	95	93	92	91	90	89	88	87	86	85	84	81	82	80	78	77	76	75	74	99	100	101	102	103	104	105	197	198	200	196	199
DEPTH IN METERS	20	21	?36	36	33	31	35	36	40	40	36	36	36	44	36	42	71	75	99	146	204	238	530	914	1097	1822	2213	1417	549	549	600	713	735
Cibicides umbonatus														.4								.4									.2		
C. wuellerstorfi																								.6	1	.9	.9	1	.4				
Cibicidina strattoni	17	24	19	20	19	25	26	28	27	27	22	30	35	33	30		14	9	7	1	.5	.1											
Cyclammina spp																									.4			.8	.2	.2	.2		
Dentalina - Nodosaria																			.2	.8								.4	.2	.3	.9	.4	.6
"Discorbis" bulbosa			.3	.1	.6	.7	1	.7	1	2	2	.2	.4	.4	.5	.6	.6		1	.4		.3											
Eggerella bradyi																							.1	.3	.4	1		.4	.2				
Elphidium advenum		.3	2		.1	.2	.3	.3							.4	.3			.2														
E. discoidale	.6	2	3	2	1	1	3	2	.8	2	2	2	2	2	2	.6	3	.7	2														
E. gunteri	2	9	5	1		.7	.3							.4	.5																		
E. poeyanum	2	.7	.8	1	.7	1	1	.3	.6		.2	.4	1	.4	.7	.6	.6			.3													
E. spp.	4	3	4	2	3	3		2	2	3	3	.7	1	.7		.6	.3	.4		.2	.3	.6	.3	.3									
Epistominella decorata																										4	9	17			.2		
E. exigua																						.1	2	2	2	2	3	2	9	9	2	1	3
E. rugosa																							1	.3			.3	2	.9	1	1	4	.8
E. vitrea		.2			.1			.1			1	.2			.2		.9	.7	.5	.6	.4	.6	.4	.6		.3					.2		
Eponides antillarum				.1	.4	2	4	4	3	.6	2	4	6	9	4	8	1	6	2	.2													
E. polius																										.3	.9	3		.2			
E. regularis																				1	4	2	2	.6		.3							
E. repandus							.7	.1				.2			.2	.3		.4															
E. tumidulus																										.3		.4					
E. turgidus																		.4		.2	.9	.4	2	1		6	19	8	3	3	.5	.6	2
Pseudoeponides umbonatus															2		.3		.2	.2	.1		.4	.3		1	2		.5	.2	.2	.4	.7
Gaudryina cf aequa													.2			.3	.3	.7	.5														
G. cf. minuta		.2	.3		.1		.7	.1		.2	.4	.2														.6				.5			
Globobulimina affinis & var																							1	.6	8	.6	1				.5	1	1
Globulina cariboea				.1		.2			.2			.2	.2																				
Glomospira charoides																								.3	.7	6	9	.8		.2		.2	
G. cf gordialis																											.9						
Goësella mississippiensis																			.5														
Guttulina australis	.6	1		.7	.3	.7	.3	.5	.6	.4	.2		.4	1															.2				
Gyroidina neosoldanii																													.2		.8		
G. orbicularis																						.1			3	2	4	4	.7	.5	.5	1	.3
Gyroidinoides soldanii altiformis																				.3	.5	.3	.1	.6		.3				.2		.6	.6
Haplophragmoides bradyi																					.1			.6	3	2	4	2	.4	2			
Höglundina elegans																			1	.2			.3						.4	.5	2	.4	.1
Hormosina sp.																						.1		.3	3	.3			.5	.5			
Karreriella bradyi																								.3	.4						.2		
Lagena spp. & related forms				.3			.7		.6	.9	.6	.5			.5			.7	.2	1	1	.9	1	1	1	2	1	1	2	1	1	.8	2
Laticarinina pauperata																								.3		2		2	.2				.3
Lenticulina peregrina																				.2			.4	.3	.4	.3			.5	.2	1	.4	
Liebusella spp.																		.7															
Loxostomum abruptum																							.1	2				.4	.9		.5		
Marginulina marginulinoides																			.5														
Miliolidae	11	5	5	5	4	4	6	3	3	4	6	5	3	3	3	6	10	4	5	1	.3	.1				.6	.3					.2	
Nodobaculariella cassis	.6	.8	.5	.4	.4	.4		.5	1	.4	.4	.2	.6				.9	2	1			.1											
Nodosaria hispida																				.2										.3	.2	.2	
Nonion formosum																		1	1	.2	.1	.1										.2	
Nonionella atlantica	5	2	4	10	6	3	3	4	4	5	5	1	2	.7	3	1	3	1	1	2	.2	1	.2							.2			
N. opima	.3	.3		1	.8	.2			.6	.4	.6	.2			.7	.3	.6	.4	1	1	1	1	.7			.3							
Nouria polymorphinoides							.3					.2	.2			.6																	
Osangularia cultur																								5	4	9	5	3	.5	.2	.8	1	.6
Peneroplidae	1	2	4	1	2	4	4	3	4	3	1	6	5	11	3	3	2	1	1														
Planorbulina mediterranensis				.1	.1			.1	.6		.4	.2	.4		2	1		1	.4														
Planulina ariminensis																							.7						.4	.6	1	1	.6
P. exorna	2	3	4	4	7	9	12	12	13	12	4	11	13	13	11	43	9	7	6	2	.8	.5											
P. foveolata																					.5	.9	.3										
Plectina apicularis																										2	2	.8	.2		.5		
Proteonina atlantica											.2	.2	.8		.7		.6	.4	.2	.2	.3	.3	.3		.4								
P. difflugiformis																							.1		3	6	2		.2	.2			
Pseudoclavulina mexicana																					.1												
P. aff. novangliae																															.5		
Pullenia bulloides																					.3	.5	.3	.3	.7	.3	2	2		.3	.5	.4	.4
P. quinqueloba																			.2	.3	.5	.3	.1	1	2	.6	2	2	.6	.3	2	.2	1
Pyrgo murrhina																			.2		.6	.1					.3						
P. cf nasutus				.5				.3			.2				.2		.6	1	1	2	.1	.9	.3										
Quinqueloculina bicostata			.3	.3	.4	2	3	2	.4	.9	2	3	.6	3	2	3		.4															
Q. compta	2	1	2	.6	1	.4	1	2	2	2	2	3	3	1	2	3	.6	.4	.2														
Q. horrida		.3		.2	.1	.7		.1	.2		.4							1	.5	.5	.1												

Table 10. Percentage distribution of benthonic Foraminifera in traverse V (pt.).

TRAVERSE	V																																
STATION	97	96	95	93	92	91	90	89	88	87	86	85	84	81	82	80	78	77	76	75	74	99	100	101	102	103	104	105	197	198	200	196	199
DEPTH IN METERS	20	21	36	36	33	31	35	36	40	40	36	36	36	44	36	42	71	75	99	146	204	238	530	914	1097	1822	2213	1417	549	549	600	713	735
Quinqueloculina lamarckiana	8	.8	1	7	1	2	3	2		1	2	3	2	3	2	3	3	3	5	2													
Q cf polygona		5		.5	3	2		4	2	.2		2		4	.7	3	6		.2														
Q sabulosa	.8	3		.5	.3	.4	1		.8		.2	.5		4		.6	.6	.4															
Q sp																	.3								.4			.4					
Rectobolivina advena						4		.1	.2	4			2		2		6		.8	.2													
R dimorpha																														.2	.5	.2	
Reophax bilocularis																											.3			.2		.2	
R distans delicatulus																										1	.3	.4		.5			
R guttifera																									.7				.2	.2			
R hispidulus																				.2	.4	.9					.9	.4	.2	.5			
R irregularis																.3																	
Reussella atlantica	.6	2	.5	2	.9	3	2	4	5	3	2	1	1	.4	4	2	8	1	1	2	.4	.5											
Robulus spp					.3				2	4			.2			.3	1	3	2	8	1	1	.8	.3	.4		.3		.4	.3	1	.4	.1
Rosalina bertheloti																			.2	.3	.1	.1											
R cf concinna	20	12	14	19	26	12	10	6	6	5	8	3	2	7	2	.6	2	3	4	4	3	5	.7	.6									
R floridana	5	8	5	5	3	2	1	9	2	1	4	.4					.6	1		.3	.1	.3		.3									
R floridensis																		7															
R parkerae				3	1				2								3		2	.5	.8	6		.3		.6		.4					
R suezensis	1		.8	9	1	2	1	1	2	1	2	9	1	4	2	6	1	2	2	1	2	9	.3										
"Rotalia" beccarii variants	4	4	6	2	3	2	2	3	2	3	2	2	2	1	1	.4	5																
"R" translucens																					.1	2	14	3	.4			2	15	19	8	5	7
Rotamorphina laevigata																				1	1	1	4	.9	1	.9	.9		.5				.1
Saccamminidae & related forms																										2	.6		2	.8			
Seabrookia earlandi																			.5	.5	.4	.5	.3	.6			.3	.4					
Sigmoilina distorta																	.3	.4	8	1	.9	1	.6							2			
S schlumbergeri																							1		4	.3					.2	.4	
S tenuis																							.3			.3				.3			
S sp																		.4															
Siphonina pulchra							.3						.2		.2		6	.4	2	.3	4	.3	.1							.2	.8		.1
Siphotextularia curta																										.3							
S rolshauseni																										6	.3	.4					
Sphaeroidina bulloides																			5	3	.5	1	2	2	2	9		8	3	2	6	4	3
S compacta																														.6	.2	.2	
Spiroloculina cf grata				3	.1		.7	.1				.2					.9	.7	.8	2													
S soldanii				.2					.4			.2	2						2	3		1											
Spiroplectammina floridana																	3	7															
Stetsonia minuta		.3	.3	.2	.4			.1	.2	.6	.2	.2										.3	.6	.3		.6		.4	.7	1			
Textularia candeiana			.3	.3	.3	.7		.1	.4		.4	.5		.7	.7	.3		.7	.2			.1											
T conica								.3									.3		.2														
T earlandi																				.2		.1		.9									
T foliacea occidentalis																			.2														
T mayori	.3	.5		1	.6	2	2	3	3	1	2	3	4	3	4	6	.7																
Textulariella spp																	.4																
Tolypammina schaudinni																													.2				
Trifarina bradyi																.6		.4		.2									.7	.8	.8	2	2
Triloculina cf brevidentata	1	.2	.8	2	.7			.5	1	1	3	2	.2	1	.2		1	.4		.5	.1	.1											
T tricarinata																						.1											
Trochammina advena																					.1				.4								
T globulosa																									6	4	.6	.4					
T cf. japonica																					.1	.1	.4		1	.9	.3		.5	.5			
T. quadriloba																									.4								
T. squamata & related spp								.1																									
T cf. tasmanica		.3															.3									.9			.2				
Uvigerina auberiana																										.3						.2	
U. hispido-costata																													5	.2	6	13	8
U. laevis																			2	4	4	5	3	1					.2				
U. parvula								.1				.2			.2		.3	1	4	3	1	1	.3	.6									
U. peregrina																					2	6	2	14	10	3	1	3		2	8	13	9
Valvulineria minuta																			.2		.9	.8	.3		.4				.4	1		.2	.7
Virgulina advena																											.6						
V. complanata	.3			.2					.2												.1	.1	1				.6		.2	.3	.2	.2	.3
V mexicana																					.1	.1	1	.3					.4	.4	.8	.2	1
V. pontoni										.2												.1	.4										
V punctata	.3	.2	.5	1	1	.6		1	1	2	5	2	.2		.9	.6		.7	1	2	1		.2										
V. tessellata																							.7	2	8		.3		1	2	.5		.6
Wiesnerella auriculata	.3			.3	.1	.2			.2		.2	.2																					
Miscellaneous spp	.1	1	1	3	1	2	1	2	.8	1	1	1	.4	1	1	.8		4	4	4	2	1	1	2	2	6	4	4	1	.4	3	1	2

Table 11. Percentage distribution of benthonic Foraminifera in traverse V (pt.).

TRAVERSE	VI																																		
STATION	73	72	71	70	69	68	67	66	65	64	63	62	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	106
DEPTH IN METERS	20	22	24	24	29	27	24	39	43	49	55	64	91		106	113	119	128	139	146	155	165	183	223	446	555	631	650	677	823	860	960	1144	1573	2697
TOTAL PLANKTONIC POPULATION	0	10	48	4	6	0	10	49	11	64	275	350	700	6 200	5 000	8 200	7 400	5 300	12 700	11 700	18 400	10 500	19 800	6 500	26 200	12 100	11 300	11 200	5 600	11 500	14 300	19 500	53 000	20 200	13 000
TOTAL BENTHONIC POPULATION	250	1 800	6 700	850	375	400	1 100	1 100	275	1 700	4 200	3 300	4 300	29 100	24 300	28 000	12 100	18 700	23 600	27 500	9 600	9 000	13 800	2 100	7 800	3 100	2 200	1 600	1 600	2 500	2 100	3 600	5 100	1 300	600
Adercotryma glomeratum																											.1		.3	.3			.3		.6
Alveolophragmium nitidum																									.1	.1					.2	.1		.2	.3
A. ringens																														.2					
A. scitulum													.1																.1	.2		.2	.2	.5	.3
A wiesneri																										.1					.6	.1		.2	
A sp										.1	.2		.1																			.1	.2		
Ammobaculites sp. B																														.2					.3
Ammodiscus spp							.2																		.1						.2	.1	.2		
Ammoscalaria pseudospiralis													.3																						
Amphistegina spp		.2			2	13	.2	6	28	50	48	19	15	2	.8	.9																			
Angulogerina jamaicensis							.4	.5		.1	.4	.1	.5	2	1	.7	2	1	1	.8	.3		.3					.1	.3						
Anomalinoides mexicana																								.2	.3		.1		.3	.5	.2	.2			
Asterigerina carinata	4	12	10	9	15	21	3	4	3	3	2	4	.8	.1		.5		.2	.1	.1		.4													
Astrononion tumidum																										.1									
Bigenerina irregularis		1	1	1	4	1	.9	2	4	.6	1	2	3	.8	.4	.2	.5			.2	.2														
B. textularioidea		.1		.5	2	.5	.7	2	3	2	3	3	6	.5	.3			.2																	
Bolivina albatrossi													.1							.1	.3	.2	.7	5	10	4	6	7	6	7	6	4	3	.5	
B. barbata																							.1												
B fragilis														.2	2	2	3	.5	3	3	2	1	2	1											
B goesii																			.1	.2		.4	.2	.4											
B lanceolata												.6	.3	.2	.1	.2	.5	2	.5	.3	1	1	2												
B lowmani							.5	.3				.1	.1	.3	1	2	3	4	4	4	8	4	7	4	2	2	2	1	.5	3	3	.4	.8		2
B minima																.5	.5		.8	1	5	6	6	7	4	.8	.1	.1			.2				
B. ordinaria																.2		.2	1	2		.2		.8	4	5	8	3	.3	.8	.8	.6	.3	.3	
B paulo															.1		.3																		
B pulchella primitiva		.7	.7		.5		.5	.1					.2	.9	.9	1	.3	1	.4	.7															
B pusilla																																			1
B. striatula spinata															.7	.5		.7	.7	.9	.5	.2													
B subaenariensis mexicana															.1	.7	.8	.2	.5	.7	3	11	17	16	.7										
B. subspinescens													.2	.6	2	.7	.3	.5	1	1	.7	1	.7	2	1	1	.9	.5	.3	.6	.2	.2			.3
B translucens																				.1	.2		.2	.6	.3	.1	.3								
B. sp																												.4	.4	.6		.3	.2	.2	
Buccella hannai		.9	2	1	.5	.5	1	1		.1			.1	.7	.4		.5	.2																	
Bulimina aculeata																								.2	.7	1	3	3	1	3	2	6	7	4	.3
B alazanensis																									.7	4	6	7	8	9	7	10	5	.5	
B marginata													.1	.1	.3	.2	.8	2	3	3	2	3	1	.8	.2										
B spicata													.1			.5	.3	.7	.5	.2		.2	.3	.4	.1	.3	.3	1	1	1	.6	.8	.8	3	
B striata mexicana																								1	2	2	2	1		.2	.4	.1	.2	3	.6
Buliminella cf bossendorfensis																			.3																
Cancris oblonga						.5	.4	.2		.1			.5	.5	1	1	1	2	1	.9	.5	.9	.3	.6											
Cassidulina carinata									.4												.3	.4	.1	.6	.3	.4	.9	.1	.1	.2			.2	2	
C aff crassa																				.2		.4	.8	.4	2	.8			.3	.2			.3	2	
C. curvata												.2	.6	2	1	3	2	.3	1	3	5	3	2	2	2	1	.3		.3						
C. laevigata								.5		.1		.1		.7	.7	.7		.2																	
C. neocarinata													.1			.2	2	1	6	7	10	4	8	4	7	4	.7	.2		.2	.6	.1			
C subglobosa & variants	.8	.2	.2	.2			1	1		.2	.2	.9	2	9	13	13	9	15	9	5	4	4	2	1	1	9	10	14	16	15	12	15	13	6	1
Cassidulinoides tenuis																										.1	.4	.5	.4	.3	.4	.3	.6		
Chilostomella oolina																			.1	.1		.2		1	.8	1	2	2	.4	.3	.4	.1	.2		.3
Cibicides corpulentus																			.3		1	4	.5	.2			.5				.2	.4	.6		
C deprimus		1	4	4	2		3	1		.1	.2	.1	.5	2	1	3	2	1	.5	.7							.1	.1							
C aff. floridanus								.2				.9	3	5	2	2	4	2	5	6	2	2	3	2	2	4	4	4	3	2	3	3	5	.8	
C io												.2	.2	.5	.5	.7		.3	.3																
C kullenbergi																																.1		.5	2
C mollis											.2	1	.9	.8	.7	.5	2	.5	.3	.3															
C. protuberans								1	.4	.3	.6	2	1	4	3	4	5	.7	.4	.8	3	4	.7												
C robertsonianus																									.1	.1	.3	.4	.4	.3		.4	2	.8	2
C rugosa																											.1	.1	.5	.5	.2	.4	.8	.5	
C umbonatus																	.3		.1	1	3	3	5	5	1										
C wuellerstorfi																														.5	1	2	3	3	9
Cibicidina strattoni	4	10	11	5	5	3	11	6	2	.6	.8	4	4	5	3	2	.8	.7	1	1	.2														
Conorbina orbicularis								.1						.1	.4	.5	.3				.2			.2											
Cyclammina spp.																											.1	.1		.2					
Dentalina - Nodosaria													.2		.1			.2	.5					.2	.6	.1	.1	.1	.1			.1		.4	

Table 12. Percentage distribution of benthonic Foraminifera in traverse VI (pt.).

TRAVERSE	VI																																		
STATION	73	72	71	70	69	68	67	66	65	64	63	62	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	106
DEPTH IN METERS	20	22	24	24	29	27	24	39	43	49	55	64	91		106	113	119	128	139	146	155	165	183	223	446	555	631	650	677	823	860	960	1144	1573	2697
"Discorbis" bulbosa		.2	.2	.7	1		2	.5				.1	.1	1	.3	.9	.3	.7	.5	.6	.7	.2													
Eggerella bradyi																									.1	.4	.2	.2	.5	.5	.2	.3	.2	.8	5
Elphidium advenum		1	.2	.5	2	2	.4	.7	.4	.1	.2		.1																						
E discoidale		2	2	3	.5	4	2	3	2	.6	.8	2	2	2	.8		.3		.7																
E gunteri		.1						.1	.4																									
E poeyanum	.8	.6	1	1	2		.5	.4		.2		.1		.5	.2		.3																	
E spp	8	3	3	1	.5	2	1	1						2	4	5	6	4	4	3	.8	.9	.1												
Epistominella decorata																														.3	.8	.3	.5	22	13
E exigua																								.2	2	8	7	8	9	7	8	7	3	3	.3
E rugosa																									.6	2	.7	2	.6	3	1	4	2		
E vitrea														.7	.1	.2	.3		.1	.1	.3				.1	.4		.2		.5	.2				
Eponides antillarum						.5		.6	.4	.6	1	2	2	.4	.3	.2																			
E polius																														1	1	.9	.3		4
E regularis																				.2				.2					.9						
E repandus		.1			.5	.5		.7	.8	5	5	.9	1									.2													
E tumidulus																											.1			.3	.2				3
E turgidus							.2					.1	.2	.2	.5	.7	.3	2	.5	2	.5	.4	1	1	.2	3	5	1	6	5	8	3	2	4	19
Pseudoeponides umbonatus												.1	.3			.2	.8	.2		.1		.2	.2		.3	.8	.8	.9	.1	.2	.4	.4	.2	2	2
Gaudryina cf aequa														.3	1	.7	.5			.3															
G. (Pseudogaudryina) atlantica																						.2		.2											
G flintii																								.2									.5	.2	
G cf minuta						.5	.7	.2																		.3	1	.4	1	.6	1	.1			
Globobulimina affinis & var																						.4	.2	.2			.4	.1	.1			.1	.2	.6	
Globulina cariboea			.7	.2	.5	1	.4	.7			.6																							
Glomospira charoides																					.2				.1	.1	.4	.2	.1	.5		.1	.6	.2	
G cf gordialis																																			.6
Guttulina australis		.3	.7	.7				.4		.1	.2	.2																						
Gypsina vesicularis		.1				.5		.3		1	1	.6	.8	.3																					
Gyroidina neosoldanii																													.3				.8	.2	
G orbicularis																						.2	.1	.6	.3	.6	1	.6	.9	1	.6	1	3	4	2
Gyroidinoides soldanii altiformis																					.2		.3		.1	.4	.2	.4	.1	.5	.6	.9	.5	.3	
Haplophragmoides bradyi																					.2					.3	1	.5	1	2	2	1	.6		2
Hoglundina elegans												.2		.5	.8	.7	1	.9	.7	.9	.3	.4	.6	.4	2	.3							2	8	1
Hormosina sp																										.1	.2		.5	.5	.2	.6	.2		
Karreriella bradyi																			.1	.1	.5			.4	.5			.1	.1	.5		.2	.2	.2	.3
Lagena spp & related forms	.8						.2	.1						.8	.8	1	.8	.2	1	1	.8	.7	.5	1	2	2	2	2	1	2	2	2	1	2	5
Laticarinina pauperata																									.2	.8	1	1	.9	1	.8	.4	.9	1	.6
Lenticulina peregrina																					.2	.2	.3	.2	.5	.5	.8	.9	.7	.8	.4	.8	.2	.2	
Liebusella spp																		.2	.4	.1	.2		.6												
Loxostomum abruptum																									.1	.5	.3	.4	1	2	2	.9	.3	2	
Marginulina marginulinoides																	.3		.3		2	.7	.1		.1										
Miliolidae	7	5	6	5	6	6	6	6	10	4	3	5	4	8	10	9	4	8	7	4	.7	1	.2	.4			.1	.1							2
Nodobaculariella cassis		2	1	2	6	2	3	1	11	3	3	5	1	.5		.2			.1	.1															
Nodosaria hispida																								.4	.9										
Nonion formosum														.2	.4		.5	.2	.5	.2	1	1	.8					.2	.3			.1	.2		
N pompilioides																																			1
Nonionella atlantica		3	4	3	1	2	1	2	.8	.1		.2	.6	2	2	2	.8	1	.5	.7	.7	.4			.3										
N opima		.2	.2			.5		.1						.4	.5	.7	.3	.5	.1	.6		.1		.4			.1			.5	.4				
Osangularia cultur																										.1	1	3	6	5	5	3	2	.2	.9
Peneroplidae	.8	7	9	9	9	17	6	4	4	3	3	5	2	.2	.4				.1															
Planorbulina mediterranensis				.2				.4	.4	.6		.4	.3	[illegible]																					
Planulina ariminensis																						.2	.5		1	1	.6	.2	.1	.5	.2				
P. exorna	.8	5	5	10	9		16	20	8	2	.8	3	2	2	3	.9	1	.2	.3	.1		.2													
P foveolata																.2	.5	.3	1	2	4	5	2	1											
Plectina apicularis																										.1		.1	.5						3
Proteonina atlantica								.1				.1																								
P. difflugiformis																				.1	.2	.2		.6		.3	.1	.1	.9	.6	.2	.1			.9
Pseudoclavulina mexicana													.7										.1		.5										
P. aff. novangliae																			.7	.2	.8		.2	.8											
Pseudoglandulina comatula																					.2	.4													
Pullenia bulloides																					.2		.5	1	1	.4	.2	.6	.3	.3	.2	1	.9	.2	.6
P quinqueloba														.2		.5			.7	.1	.5	.2	.2	.2	.1	.1	.4	.6	.5	.2	.8	1	.9	1	1
P sp																																.1			
Pyrgo murrhina								.1									.3								.1					.2	.6	.1		.6	
P cf. nasutus								.2					.3	.4	.8	.7	.3	.5	.5		.3	.4	.2	.4	.2										
Quinqueloculina bicostata		.1		.2		1	.2	.8	2	.6	1	.2	.4	.1																				
Q compta		.5		.7	2	2	.7	.7	.8	.7		1	.5	.4	.1	.2	.5		.3															
Q. horrida								.4		.7	.6	1	5	1	.4	.2	.5	.2	1	.7	1	.5	.7												
Q lamarckiana		2	.5	.2	2	4	.9	4	8	7	11	8	6	2	.9	.7	1		.2	.2	.8		.6												
Q. cf. polygona		.7	.2		.5	.5		.1		.2	.4	.7	.2	.2																				

Table 13. Percentage distribution of benthonic Foraminifera in traverse VI (pt.).

TRAVERSE	VI																																		
STATION	73	72	71	70	69	68	67	66	65	64	63	62	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	106
DEPTH IN METERS	20	22	24	24	29	27	24	39	43	49	55	64	91		106	113	119	128	139	146	155	165	183	223	446	555	631	650	677	823	860	960	1144	1573	2887
Quinqueloculina sabulosa	.8	.1	.2	1			.2					.2	.1	.1																					
Q. venusta																																			.3
Q. sp.																																		.3	.6
Rectobolivina advena			.5	.2			.4	.1				.1		.8	1	.5	.3	.3	.1	.2			.1												
R. dimorpha																									.1	.1	.2	.1		.2			.3		
Reophax bilocularis																									.3	.3	.1		.4	.2				.2	
R distans delicatulus																															.2				
R. hispidulus															.1										.1			.7	.1	.2	.4				
R. irregularis											.2	11	9		.1						.7	.2	.2												
R. scorpiurus																					.2				.3										.3
R. sp.																										.1									
Reussella atlantica		.9	1	1	.5	2	2	5	3	.7		.7	.4	.9	2	1	.5	.5	.8	.7	.2	.2	.1												
Robertina bradyi															.1								.2											.2	
Robulus spp							.2	.6	.4	4	4	2	5	1	1	2	.8	.9	3	2	2	4	3	3	1	.3	.7	.2	.1		.2			.2	
Rosalina bertheloti														.4	.4	.9	2	.9	2	1	2	1	.8	.2											
R. cf concinna	14	15	19	23	15	5	18	7	.4	.5		.6	2	14	12	11	15	12	8	9	.8	.4	.2	.8											
R. floridana	15	7	10	7	2	.5	4	2		.2	.2	.2	.4	3	3	2		.5	.7	.8															
R floridensis									.4	.8	1	2	.8	.5		.2				.1															
R. parkerae	.8	.3	.2					.5				.1		.2	.9	1		.7	.8	.6		.4	.1												
R. suezensis		2	.2			.5	.5	.3				.1		1	1	1	1	2	3	4	2	2	1	.4											
"Rotalia" beccarii variants	34	6	1	2	1		2	.7	.8				.2	.1	.1	.2		.2																	
"R." translucens																						.2		5	15	20	8	7	7	4	4	3	2	2	
Rotamorphina laevigata														.1				.2	.4	.2	.2	.2	.7	1	.2	.9	.8	.7	.4	1	.4	.6		.3	
Saccamminidae & related forms																								.2		.4	.5		.6	.2	.6	.1	.3		1
Seabrookia earlandi															.3				.5	.2	.2		.2			.3	.2				.2	.1		.2	
Sigmoilina distorta													.4		.8	.9	1	2	1	1	1	1	3	.6	.3										
S. schlumbergeri																									.6		.5	.4	.4		.2	.1	.5	1	.3
S. tenuis																									.6	.1	.2	.1	.1		.2	.1	.5	.6	
S. sp.						1		.2			.2	.6									.2														
Siphonina bradyana																					1	.5	.8	.4	.8	.3	.1	.2							
S pulchra								.2		.2		.4	.2	.9	1	1	2	1	2	2	3	2	.8	.6	.3		.2		.1						
Siphotextularia curta																																	.2	.2	.3
S. rolshauseni																																	.3		.3
Sphaeroidina bulloides															.3		.3	.2	.4	.3	.3	.4	.2	1	4	2	2	3	3	2	2	1	.5	.6	.3
S. compacta																					.2									.3		.2		.5	
Spirillina vivipara						.5		.1		.5				.8	.4	.2	.3	.7	.4	.5	.5	.2	.1												
Spiroloculina cf. grata		.6	1	1			.4	.5						.4	1	.7	1	.9	.1	.2															
S soldanii		.1	.2	.2				.1					.1	.4	.4	.2		.2		.1				.2											
Spiroplectammina floridana								.1	.4	.3	.6	1	2																						
Stetsonia minuta		.5	.2				.5	.2						.3	1	1	1	1	.3	.6					.3	2	.8	.2	1	.5	.6	.3	.9	.2	.3
Textularia candeiana		1	.5	2			.9	1	.4	.3	.2	.4	.4	.3						.1			.4	.4											
T. conica		.3				1	.5	1	2	2	2	.5	1	1		.2																			
T. foliacea occidentalis												.6	.4	.5		.2		.5	.6	.2	.3	1			.2										
T mayori		.1	.2	.2		1	.2	1	.4	.1	.2	.5	.8	.1						.1		.4	.1												
Textulariella spp										.1		1	2	.2																					
Tolypammina schaudinni																																			
Trifarina bradyi															.1			.2							.6	.9	.5	.7	1		.8	.1	.2		
Triloculina cf. brevidentata	.8	2	.5	2	.5		2	1		.2	.2		.5	.5							.3														
T tricarinata																																		.5	.3
Trochammina advena																											.4			.8					
T. globulosa																																	.3		1
T. cf. japonica																													.6			.1	.2		
T. squamata & related spp.	5	1		.7	2		1	.1	.4																										
T. cf. tasmanica																											.2					.1			
Uvigerina auberiana																									.1		.2					.1	.2		
U. flintii																	.3	.3	1	.7	1	2	.7												
U. hispido-costata																								3	10	.6	.6								
U laevis													.2	1	3	3	3	7	4	6	4	5	7	8											
U. parvula														.8	2	2	2	4	4	4	6	7	6	2	.2										
U. peregrina																									2	2	7	14	10	7	10	17	25	9	
Valvulineria minuta																.2		.6			.3		.2	.6	.5	1	.1			.2		.3	.3		
Virgulina advena																																			2
V. complanata													.1	.1	.3		.5	.2	.1	.1				.4	.4	.3	.4	.2	.5	.3	.4	.1	.2		
V mexicana																.2		.2							.7	.1	.7	.2	.1						
V. pontoni														.1			.3				.3														
V punctulata		.2	1	.2	.5		1	1					.2	2	2	2	1	2	.8	.6															
V. tessellata																									.3	1	1	.5	1	.2	1	.3			
Wiesnerella auriculata	2	.8	.7	.2		1	.7	.4						.1																					
Miscellaneous spp.	.6	3	1	1	5	2	1	2	1	3	3	4	4	3	2	2	6	4	2	3	3	3	4	5	5	4	2	2	.3	.2	3	2	1	3	5

Table 14. Percentage distribution of benthonic Foraminifera in traverse VI (pt.).

TRAVERSE	VII																		
STATION	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	107
DEPTH IN METERS	22	31	46	49	86	146	183	186	237	274	274	320	347	457	585	732	878	2999	3017
TOTAL PLANKTONIC POPULATION	12	8	34	450	150	2 300	27 100	12 800	19 500	14 000	14 800	20 700	60 900	200 000	56 800	16 000	34 600	47 300	40 400
TOTAL BENTHONIC POPULATION	1 900	1 400	1 500	17 100	2 400	5 300	46 700	12 800	27 900	6 600	6 400	3 100	10 300	7 400	5 600	4 500	4 000	1 300	1 600
Adercotryma glomeratum											.1					.2	.1	2	3
Alveolophragmium nitidum													.1	.1			.2	.2	
A. subglobosum																		.5	
A sp				.1															
Ammobaculites sp B																		.9	.5
Ammodiscus spp																.1			
Ammoscalaria pseudospiralis	.2	.8																	
A tenuimargo																		1	.1
Amphistegina spp	.2		5	1	11	16													
Angulogerina bella			.3	.6		.1													
A jamaicensis	.5		.3	.2	.8	.3													
Anomalinoides mexicana											.4	.3	.2	.5	.9	1	.9		
Asterigerina carinata	.8	6	3	15	7	1													
Astrononion tumidum												.1		.2	.1	.3			
Bigenerina irregularis	1	5	.7	.7	.3	.3													
B. textularioidea	.2	.6	6	2	3	2													
Bolivina albatrossi							.7	.9	3	5	7	8	10	7	3	5	3		
B barbata						.1													
B fragilis				.1	.3	.7													
B goesii						.1	.3	1	1	.2									
B lanceolata			.1		.2	.6	3	2											
B lowmani	.3				.2	2	8	2	4	1	3	.9	1	.8	1	1	.7	2	1
B. minima						.1	3	2	6	2	6	6	6	3	.9	.9	2		
B. ordinaria						.2	4	3	7	3	4	4	15	8	8	1	.3		.5
B. paula	.2	.3																.2	
B pulchella primitiva	.4		.5	.1	.3	.4	.1	.1	.1								.1	2	.5
B. striatula spinata						3	.7	1	.5										
B. subaenariensis mexicana							4	12	10	11	9	2	.3						
B subspinescens					.2	.3	.8	1	3	2	2	2	2	1	.9	.4	.2	.2	
B translucens										.2	.4	.8	.2	.4	.4				
B. sp.														.1	.6	.5	.7		
Buccella hannai	.5	.8	.1	.2	.3		.1												
Bulimina aculeata											.1	.1	1	.8	3	2	3		
B alazanensis														1	3	5	6	.2	
B marginata							.1	1	1	.7	.3	.3	.2						
B spicata									.8			.6	.6	.2	.3	.3	.7		
B. striata mexicana												.1	.1	.2					
Cancris oblonga			.3	.1	.3	.6	.1		.3										
Cassidulina carinata				.1			2		1	4	1	2	1	3					.5
C. aff. crassa						.4	.6	.8	.2				.9	2	.3		.1		
C. curvata					.4	.7	4	5	5	1	2	1	1	4	2				.5
C. laevigata												.1							
C neocarinata					.2	3	7	11	8	2	5	9	5		2	.5	.1		
C subglobosa & variants	.2		.7	.6	3	9	4	2	6	4	7	6	4	6	9	16	9	1	1
Cassidulinoides tenuis													.1	1	1	.3	.3		
Chilostomella oolina										.2		.5	.2	.8	1	.7	.4		
Cibicides corpulentus						.1	.1	1	.3	.5	.1	.4	.2	.1	.3		.1		
C. deprimus	1	1	.7	.7	1	.9	.1	.4	.1			.3	.1	.2			.3		
C. aff. floridanus					.6	2	7	4	.9	5	2	3	2	1	3	2	1		
C. io					.1														
C. kullenbergi																	.6	1	.5
C. mollis						.3	.1							.2					
C. protuberans	.3		.5	.8	.9	4	1	4	.9	1						.3	.3		
C. robertsonianus										1	.1	.1	.1		.7	.3	.4	2	2
C. rugosa																3	.5		
C umbonatus							1	3	2	.5	2	3	1						
C. wuellerstorfi														.1	.9	.5	1	21	15
Cibicidina strattoni	9	19	5	6	2	.4													
Conorbina orbicularis					.3	.2													
Dentalina - Nodosaria										.2		.3	.4	.3		.1	.2		

Table 15. Percentage distribution of benthonic Foraminifera in traverse VII (pt.).

TRAVERSE	VII																		
STATION	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	107
DEPTH IN METERS	22	31	46	49	86	146	183	186	237	274	274	320	347	457	585	732	878	2999	3017
"Discorbis" bulbosa			.4			.1	.1												
Eggerella bradyi																.2	.4	3	1
Elphidium advenum	.5	2	.7	.6	.5														
E. discoidale	2	7	.7	.6	.1	.1													
E. gunteri	.8			.4															
E poeyanum	1	.6																	
E spp.	4	1	1	.9	5	2	.3												
Epistominella decorata																		13	18
E exigua													.4	3	6	8	14		.5
E rugosa												.1	.9	2	1	3	2		1
E. vitrea				.1		.5	.3	.2			.3	.1	.2	.4	.4	.2			
Eponides antillarum	.2		3	.6		.1													
E. polius																1	.5	4	5
E. regularis																			1
E. repandus		.3	.3		.3	3													
E. tumidulus																		3	3
E turgidus							2	.9	4	1	4	1	.4	2	4	7	5	5	8
Pseudoeponides umbonatus								.1		1	.6	.5	.2	.3	.1	.4	.3	3	3
Gaudryina cf. aequa				.2															
G (Pseudogaudryina) atlantica								.1	.1	.5									
G. flintii																	.2		
G. cf. minuta	.5	1							.1		.1	.1	.2	.1	.1	.1	.2		
Globobulimina affinis & variant									.1								.1	.3	1
Globulina caribaea		.6	1																
Glomospira charoides								.1		.2			.3					.5	.5
G. cf. gordialis																		.3	1
Guttulina australis	.1	.3	.3																
Gypsina vesicularis			.5	.5	.4	.3													
Gyroidina neosoldanii								.1									.1	.8	
G. orbicularis							.3		.5	.2	.6	.1	.4	.2	.4	2	2	.2	
Gyroidinoides soldanii altiformis								.2	.1		.3	.3	.2	.6	.6	.7	.3		
Haplophragmoides bradyi													.1	.1	.1	.6	.3	2	2
Höglundina elegans						.2	.3	1	.8	.5	.3	.5	.4	1	1		1		5
Hormosina sp											.1	.1				.2			
Karreriella bradyi								.4		.7	.3		.2			.1	.4		
Lagena spp & related forms	.2		.8	.2	.2	.6	.4	1	1	2	.8	1	.6	2	2	3	3	6	3
Laticarinina pauperata													.2		.3	.9	1	.9	
Lenticulina peregrina							.1	.1	.2		.3	.5	.5	.4	.3	.8	1		
Liebusella spp					.2	1		.6	.2	.2									
Loxostomum abruptum														.1	.1	.6	3	.3	.5
Marginulina marginulinoides								.2	.1										
Miliolidae	14	9	10	15	11	6	2	1	.8		.1	.3	.2						
Nodobaculariella cassis	.5	.3	1	7	2	.8													
Nodosaria hispida												.1	.2	.3					
Nonion formosum					.1	.1	.3	.8	.1		.3				.1				
N pompilioides																		2	2
Nonionella atlantica	2	2	1	1	1	.7					.1	.1							
N opima	.9		.3																
Nouria polymorphinoides	.1	.3	.1																
Osangularia cultur															.4	3	3	.3	.5
Peneroplidae	2	4	14	10	5	.5													
Planorbulina mediterranensis		.3	.9	.3	.6	.3													
Planulina ariminensis								1	.6	.5	.3	.4	.9	2	1	.2			
P. exorna	2	13	9	8	3	2	.4	.6	.3										
P. foveolata							4	3	3	3	2	.9	.2						
Plectina apicularis									.2					.1			.1	3	2
Proteonina atlantica	.1							.1		.2									1
P. difflugiformis													.1					1	
Pseudoclavulina mexicana					.2		.1	.2	.3	.5	.3	.4	.1	.3					
P. aff. novangliae						.1	.3	.1		1	.3	.3	.1						
Pseudoglandulina comatula						.2		.1	.1										
Pullenia bulloides						.3	.3	.2	.9	.7	.9	.8	.6	.7	.3	.5	.5	1	1
P quinqueloba						.2	.3	.6	.1	.5	.4	.4	.2	.7	.8	1	2	.9	2
P sp																		.3	
Pyrgo murrhina									.1	.2	.4	.1	.3	.2		.4	.8	.6	
P cf nasutus	.4			.2		.3						.1							
Quinqueloculina bicostata	.3	.6	2	.1	.2														
Q. compta	1	2	.8	.1	.2	.3													
Q. horrida	.3		2	1	.5	.3			.1			.1	.1						

Table 16. Percentage distribution of benthonic Foraminifera in traverse VII (pt.).

TRAVERSE	VII																		
STATION	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	107
DEPTH IN METERS	22	31	46	49	86	146	183	186	237	274	274	320	347	457	585	732	878	2999	3017
Quinqueloculina lamarckiana	3	1	4	3	2	2	.1		.1		.1								
Q cf polygona			.3			.2													
Q. sabulosa	.2	.6		.2															
Q. venusta																		.9	.5
Rectobolivina advena		.3	.1	.8	.7	.6	.3												
R dimorpha															.1	.1	.2		
Reophax bilocularis												.4	.1	.3		.4	.4		
R distans delicatulus																		3	1
R guttifera										.2			.1						
R hispidulus			.1					.1	.1	.2	.1	.3	.2	.2				.8	.5
R irregularis			2	2	1	1													
R scorpiurus																		.5	
Reussella atlantica	1	2	3	1	.6	1	.4	.1											
Robertina bradyi							.1					.1							
Robulus ssp			4	1	1	2	3	3	3	2	1	1	1	.8	.2	.2	.1		
Rosalina bertheloti					.1	.4	2	1	.9	.7	.3								
R cf concinna	13	7	4	8	13	5	2	.4		1	.3	.4	.2	.1			.1		
R floridana	3	.6	.4	.2	.9	.1	.3												
R floridensis				.3	.4	.8													
R parkerae	.4	.6		.1	.7	.6	.1		.1										.5
R suezensis		.8	.9	1	1	.9	2	2	2	1	.3	.3							
"Rotalia" beccarii variants	24	4	1	.5	.1														
"R" translucens							.1		1	10	14	16	19	25	27	11	5	.2	.5
Rotamorphina laevigata						.1	.1	.9	.7	.5	2	.3	.1	.4		.6	.9		
Saccamminidae & related forms																.1			
Seabrookia earlandi			.1		.1	.2			.1	.7	.5	.5	.1	.4	.5	.4			
Sigmoilina distorta					.2	.1	1	.5	.5	1	2	2	2	.2					
S schlumbergeri								.4			.1		.5	.5	.4	.2	.3	1	
S tenuis												.1	.1	.1	.4	.3	.6		
S sp					1	3			.2										
Siphonina bradyana								.4				.5	.4	.6	.1				
S pulchra				.3	.1	.7	2	2	.8	1	.5	.1	.1	.4					
Siphotextularia rolshauseni																		.3	1
Sphaeroidina bulloides						.3		.5	.6	.7	1	2	.9	1	.9	2	2		.5
Spirillina vivipara	.1			.2	1	.7	.3												
Spiroloculina cf grata	.5		.3		.3	.2													
S soldanii	.1	.3	.1			.2													
Spiroplectammina floridana			.5	.2	2	.3													
Stetsonia minuta						.1	.3	.1	.3				.2	.7	.4	.5	.6		
Textularia candeiana	.8	.3	1	2	.7	.2	.3	.2	.2	1	.4	.3	.5						
T conica	.2	.8	1	.5		1		.4		.2	.3								
T foliacea occidentalis					.2	.4		.2											
T mayori	1	2	.7	.9															
Textulariella spp				.4	2	2		.1											
Tolypammina schaudinni																			.5
Trifarina bradyi										.2		1	1	1	2	.9	.9		
Triloculina tricarinata												.1							
Trochammina globulosa																		1	
T cf japonica						.1						.1				.2			
T. quadriloba									.1										
T squamata & related spp	1			.3	.1														
Uvigerina auberiana												.4			.1		.1	.2	
U. flintii					.3	.3	.4	.6	.4	1	.3	.1	.1						
U hispido-costata												2	6	3	.1				
U laevis					.2	1	6	4	6	9	5	3	.6	.1					
U parvula						.4	9	8	4	3	2	.8	.2						
U. peregrina									.3	2	2	3	2	1	2	6	14	.2	
Valvulineria mexicana																			.5
V minuta						.2	.3	.2	1	1	.9	.9	.7	.8	.6	.7	.3		.5
Virgulina advena																		.8	
V. complanata					.1		.3	.2	.1		.5	.3	.2	.3	.7	1	.5	.2	
V mexicana												.6	.5	.3			.1		.5
V. pontoni	.2		.1																
V punctata	.9	.3	.8	.3	.6	.9		.1											
V tessellata														.6	.6	.7	.4		
Wiesnerella auriculata	.3	.3			.8	.1		.1											
Miscellaneous spp.	2	1	2	1	5	3	6	4	2	6	2	3	2	3	2			5	5

Table 17. Percentage distribution of benthonic Foraminifera in traverse VII (pt.).

TRAVERSE	VIII																								
STATION	172	171	170	169	168	167	166	165	164	163	161	160	159	158	157	156	155	154	153	152	151	150	149	148	146
DEPTH IN METERS	212	15	20	20	22	26	29	31	31	36	35	46	51	60	62	58	79	117	146	183	366	585	914	1730	3164
TOTAL PLANKTONIC POPULATION	2	0	0	0	0	0	0	0	64	200	1 700	88	175	650	1 600	500	3 000	37 200	38 500	38 500	25 900	16 200	14 900	15 700	65 000
TOTAL BENTHONIC POPULATION	800	2 100	5 400	20 500	900	2 300	5 800	36 400	29 900	18 900	60 500	4 900	3 600	5 700	17 400	22 900	7 500	19 400	19 800	23 700	11 100	3 300	3 000	1 600	1 600
Adercotryma glomeratum																									2
Alveolophragmium nitidum																							.3	.2	
A. subglobosum																							.3	.2	
A. wiesneri																							.4		
Ammobaculites sp B																								.2	2
Ammodiscus spp.																							.1		
Ammoscalaria pseudospiralis																				.3					
A. tenuimargo																									2
Amphistegina spp.				.8	3	.4	.2		.1	3	2	2	25	4	2	3	17	1							
Angulogerina bella																	.2	.5		.3					
A. jamaicensis											.1			.4	.1					.3				.2	
Anomalinoides mexicana																						.5	.5	.5	
Asterigerina carinata	5	15	36	18	24	31	28	8	5	2	.1	7	7	8	19	31	2		.3	.3					
Astrononion tumidum																					.1	.4	.4		
Bigenerina irregularis	.3		2	.8	.2	.7	.8	1	2	3	2	1	1	2	2	.6	1	.5		.6					
B. textularioidea			.1			.6	.7	1	1	2	.7	2	9	9	5	.4	3			.3					
Bolivina albatrossi					.2															.3	6	4	5	.5	
B. fragilis														.1	.3			.3	.3	2					
B. goesii																			4	1					
B. lanceolata															.1			2	4	2	.3				
B. lowmani										.2	.3	.2	.1		.1	.1	.2	2	2	4	2	2	.4	8	.8
B. minima																			4	12	14	2	.1		
B. ordinaria																			.3		5	5	.8		.5
B. paula																								.7	.8
B. pulchella primitiva				2			.3	.2	.4	.2		.2	.1	.4					.3			.1			
B. pusilla																								2	.2
B. striatula spinata																					.3				
B. subaenariensis mexicana																			.3	.8					
B. subspinescens														.3	.1	.1	.4	2	1	2	2	.6	.4		.5
B. translucens																						.2			
B. sp.																						1	.8	.7	
Buccella hannai		.2	2	1	.4	.1	.3	1	1	2	1	.2		.3	.3	1									
Bulimina aculeata																					2	1	3	9	
B. alazanensis																						2	7	3	.2
B. spicata																			.6		.3	.1	1	.7	
B. striata mexicana																					.1			1	
Cancris oblonga									.1	.3	.6	1	.8	.7	.7		.2	.5	2						
Cassidulina carinata											.2	.2	.2		.1		.6		.3	.8	3	.2		5	.2
C. aff. crassa																				.3	2	.6			
C. curvata														.7	1	.6	4	4	3	3	.3	2			
C. laevigata																	6	.3						.2	
C. neocarinata																	.2	.3	5	3	6	2			
C. subglobosa & variants	.3										.3	.3	1	.6	.3	.4		8	4	5	6	10	9	10	5
Cassidulinoides tenuis																						1	.8		
Chilostomella oolina																					.4	2	.4		
Cibicides corpulentus																		.2	.6	.3		.8	.5		
C. deprimus	.5	3	2	6	19	4	6	7	4	2	2	1	.5	.4	1	.4	.8	1							
C. aff. floridanus																	.8	4	3	4	2	1	2	.2	
C. io													.2	.4	.5	1	.4	.7							
C. kullenbergi																	.4					.2	.3	1	.5
C. mollis														.3	.6	.4		1	.6						
C. protuberans							.1			.3	1	2	2	3	3	2	11	10	6	7	.4	.2			
C. robertsonianus																						.5	.9	.5	2
C. rugosa																						.1	.8	.2	
C. umbonatus										.2									.3	2	3	.4			
C. wuellerstorfi																						1	2	1	12
Cibicidina strattoni		.5	.8	5	2	3	4	8	8	8	4	2	1	4	6	3	1	2	1						

Table 18. Percentage distribution of benthonic Foraminifera in traverse VIII (pt.).

TRAVERSE	VIII																								
STATION	172	171	170	169	168	167	166	165	164	163	161	160	159	158	157	156	155	154	153	152	151	150	149	148	146
DEPTH IN METERS	12	15	20	20	22	26	29	31	31	36	35	46	51	60	62	58	79	117	146	183	366	585	914	1730	3164
Conorbina orbicularis							.3	.2	.3		1	.8	.7	.6	.3			.7	.6						
Cyclammina spp																						.1			
Dentalina - Nodosaria															.1		.2		.6			.2	.3	4	
"Discorbis" bulbosa								.3	.1		.4	.2	.1		.1		.2	1		.8					
Eggerella bradyi																				.3			.1	1	.8
Elphidium advenum	.3	.2	2	2	.7	1	.6	.3	.2	.8	.2	.7	.4		.6	.8		.3							
E. discoidale	.8	.5	2	3	1	1	3	3	5	6	2	.3	.5	1	.8	.8				.3					
E. gunteri	1	.3	.3	.7	.4	.4	.4	1	3	2	2	1	.4	.7	1	.3	.6	.5		.3					
E. poeyanum	2	.4	1	1	.2	.1	.4	1	.4	.8	1	.3	.5	.3	.1	.1									
E spp	2	3	2	4	.2	.9	2	1	.8	1	3	1	.3	.4	.8	.1	.4	.8							
Epistominella decorata																								3	13
E. exigua																					.6	3	9	.5	3
E. rugosa																					2	1	.7		
E. vitrea																						.8	.4	1	
Eponides antillarum							.3	.5	.5	1	.1	.7	.8	1	1	.8	.2								
E. polius																						.1	.3	.7	5
E. repandus					.9	.2	.1	.1	.3	.2		.2	2	.3	.2	.3	.4								
E. tumidulus																									4
E. turgidus																		.3		.3	.1	3	5	3	8
Pseudoeponides umbonatus																					.3	.2	.3	.2	2
Gaudryina cf. aequa											.8	.2		.4		.1	.6	.8							
G. (Pseudogaudryina) atlantica																			.6						
G. flintii																							.3	1	
G. cf. minuta																						.4	.3		
Globobulimina affinis & variant																									.2
Globulina caribaea	.5	.1		.2	.2		.2					.2				.3									
Glomospira charoides																							.5	.7	1
G. cf. gordialis																									1
Guttulina australis	.3	.1	.3	1		.3	.4	.4	.4	.5	.3	.5	.1	.1	.4		.2								
Gypsina vesicularis							.1	.2		.2		.7	.8	.3	.4	.1	.8								
Gyroidina neosoldanii																									.5
G. orbicularis																				.3	.3	.1	2	2	2
Gyroidinoides soldanii altiformis																					.4	1	.4		.2
Haplophragmoides bradyi																						.4	.4		1
Höglundina elegans																		.2	.3	.5	.9	1	1	4	
Karreriella bradyi																					.1	.2	.4		
Lagena spp. & related forms										.2				.1	.2	.1	.2	.2		1	1	2	3	2	5
Laticarinina pauperata																					.1	.1	.8	.7	2
Lenticulina peregrina											.1				.1						.4	.8	.7		
Liebusella spp																			.3						
Loxostomum abruptum																		.3				.5	2	3	.2
Marginulina marginulinoides																		.3							
Miliolidae	42	21	9	11	5	8	16	14	14	15	20	18	5	10	13	11	6	7	3	2	.3	.1		.5	
Nodobaculariella cassis	4	2	.6	.5	.9	4	4	2	2	2	3	5	1	3	3	4	2	.5		.3					
Nodosaria hispida																					.4	.1			
Nonion formosum															.1		.2	.7		.3		.2	.1	1	
N. pompilioides																									2
Nonionella atlantica		.4			.2		.8	2	2	3	4	2	.8	1	1	.6	.4	.7	.6	.3					
Nouria polymorphinoides						.1	.1		.1																
Osangularia cultur																						.2	2	1	
Peneroplidae	16	16	16	17	28	26	10	13	18	8	6	18	8	19	8	16	2	1		.3					
Planorbulina mediterranensis	.8	.1	.1	.1	.2			.1	.1	1	.6	.2	.4	.4	.6	.3	.8	.8	.6						
Planulina ariminensis																				1	1	.7			
P. exorna						.1	.3	6	8	11	15	5	4	8	11	11	8	5	.6	.5	.3				
P. foveolata																	.4	.7	2	2					
Plectina apicularis																						.1		.2	2
Proteonina difflugiformis													.1									.1		.2	1
Pseudoclavulina mexicana																		.2							
P. aff. novangliae																		.3	1		.1				
Pseudoglandulina comatula																				.3					
Pullenia bulloides																				.3	1	.5	.3	1	.8
P. quinqueloba																		.2	.3	.3	.4	.7	1	.2	2
P. sp.																								.2	.2
Pyrgo murrhina																					.4	.1	.4	.5	2
P. cf. nasutus								.1	.1	.3			.5	.1	.2		.2	.5	1		.7				
Quinqueloculina bicostata			.5	.3	.7	2	.8	.5	.6	1	.4	.3	2	.4	.3		.2		.3						
Q. compta	1	.1	6	3	3	2	2	3	3	2	1	2	1	.7	.3	.1	.2								
Q. horrida												.2	.4	.8	.9		.8	.2	.3		.9				

Table 19. Percentage distribution of benthonic Foraminifera in traverse VIII (pt.).

TRAVERSE	VIII																								
STATION	172	171	170	169	168	167	166	165	164	163	161	160	159	158	157	156	155	154	153	152	151	150	149	148	146
DEPTH IN METERS	12	15	20	20	22	26	29	31	31	36	35	46	51	60	62	58	79	117	146	183	366	585	914	1730	3164
Quinqueloculina lamarckiana	.3	.5	6	4	4	5	3	5	7	5	5	5	6	5	4	3	5	1	2						
Q. cf. polygona	1	.1	.6	.4		.3		.2	.3	.2	.5	.2		.4			.6	.2							
Q. sabulosa			.4																						
Q. venusta																									2
Q. sp.																						.2	.4	1	.5
Rectobolivina advena									.2	.2	.5	.2	.2				.2				.1				
R. dimorpha																						.1	.1		
Reophax bilocularis																						.6	.9		
R. distans delicatulus																									.8
R. hispidulus																							.3	.2	.5
R. irregularis												.2	.9	1	.6	.4	2	2	6	1					
Reussella atlantica							.3	1	1	2	2	.8	2	1	1	1	4	.8	1						
Robertina bradyi																		.2			.1			.2	
Robulus spp.								.1					.5	.3	.7		.6		3	2	2	.1	.3	.7	
Rosalina bertheloti											.2	.3						.7	3	3	.3				
R. cf. concinna	13	28	5	11	3	4	6	4	1	1	4	2	2	.4	.4	.4	.6	1	2	1			.3		
R. floridana	1	4	2	5	.9	3	3	5	5	2	2	4	.2	.4	.6	.3	.6	1							
R. floridensis														.1											
R. parkerae						.1	.4	.3	.2	.2	.6	1	1	.1	.7		.2	.5	.6	.8		.1			
R. suezensis							.4	.9	.5		1	2	2	1	.8	.7	.4	6	5	6	.1				
"Rotalia" beccarii variants	1	1	.5	.6	.2	.2	.3	.5	.1			.3	.1		.7		.2	2							
"R." translucens																					14	21	5	1	
Rotamorphina laevigata																			.3	3	.1	.5	.7		.2
Saccamminidae & related forms																									
Seabrookia earlandi																		.5			.4	.1	.3		
Sigmoilina distorta																		1	.3	.3	.6				
S. schlumbergeri																						.5	2	.7	.8
S. tenuis																							.4	.7	
S. sp.				.3	.2				.1				.4		.4		.8								
Siphonina bradyana												.2		.1	.4			.7	1	.8	.9	.6			
S. pulchra											.3	.2		.4	.2		.6	.8	1	2	.1				
Siphotextularia curta																							.1		
S. rolshauseni																									.2
Sphaeroidina bulloides																				.3	2	2	1		
S. compacta																		.3			.4				
Spirillina vivipara							.1	.1			.2				.1		.2	.7	.6						
Spiroloculina cf. grata			.2	.4		.1	.2	.3		.3	.3	.2		.3				1		.8	.1	.2			
S. soldanii				.1	.2	.1	.1	.2	.1		.3	.2		.3	.2		.2	1	.3	1					
Spiroplectammina floridana											.1		.2	.7	.6	.3	2	.2							
Stetsonia minuta																				.5		.4	.4	.2	
Textularia candeiana	3	.7	1	1	.4	.4	1	2	1	4	.5	1	1	2	2	1	2	2	.3	.3				.2	
T. conica	.3		.2				.1	.4	.3	.8	.5	.8	1	1	.8		1	.7	.6						
T. foliacea occidentalis															.1		.6	.8	1	.3				.2	
T. mayori								.8	.5	1	2	.2	.2	.1	.3	.1	.2	1	.3						
Textulariella spp.										.2			.7					.2		.3					
Tolypammina schaudinni																						.1		.2	.5
Trifarina bradyi														.1							2	2	2	.9	
Triloculina cf. brevidentata	2	.5	.7	.2		.4	.7	1	.6	1	1	.7	.8	.6	.7	.6	.6	2	.6	.5					
T. tricarinata																						.2			
Trochammina globulosa																									1
T. quadriloba																									.2
T. squamata & related spp.		.4				.2					.2	.2	.1				.2								
Uvigerina auberiana																					.1			9	.8
U. flintii																		.7	5	2					
U. hispido-costata																					.7				
U. laevis																		2	3	5	1			.2	
U. parvula																		2	1	3	.6				
U. peregrina																					4	4	14	4	.2
Valvulineria mexicana																							.1		
V. minuta																	.2	.3	1	.3	.7	.6	.3		
Virgulina advena																								.2	.2
V. complanata																						.2	.7	.2	.2
V. mexicana																					.3	.2			
V. pontoni																		.2							
V. punctata		.1		.1				.7	.3	2	1	1	.4	.3	.5	.1		.5	.3						
V. tessellata																						1	.4		
Wiesnerella auriculata							.5	.5	.2	.2	.2	.5	.1					.2	.3						
Miscellaneous spp.	1	1	.7		.7	.3	1	2	1	.7	2	2	2	1		1	2	2	6	3	2	6	1	3	4

Table 20. Percentage distribution of benthonic Foraminifera in traverse VIII (pt.).

TRAVERSE	IX								X									XI													
STATION	138	140	141	142	144	145	137	108	136	134	131	130	133	129	128	127	126	117	118	116	124	123	122	121	120	113	112	110	111	1	2
DEPTH IN METERS	183	256	320	421	914	2268	3160	3072	1051	950	1920	3200		3180	1737	2150	1317	139	146	155	914	1326	1829	2560	3246	2280	3283	3218	3251	3237	3237
TOTAL PLANKTONIC POPULATION	20 000	80 000	60 000	100 000	40 000	30 000	100 000	80 000	200 000	60 000	10 000	10 000	80 000	90 000	80 000	200 000	30 000	40 000	50 000	60 000	100 000	30 000	70 000	50 000	20 000	10 000	60 000	100 000	40 000	20 000	70 000
TOTAL BENTHONIC POPULATION	9 800	8 800	26 800	32 400	4 200	900	1 500	1 700	3 900	3 500	1 100	275	1 100	2 000	2 800	4 300	1 300	12 100	12 400	1 800	8 000	1 100	1 300	900	375	325	1 600	1 400	600	275	625
Adercotryma glomeratum						.2	2	1	.1			1	.7	5	1		.2				.1	.1	.3		5	.6	1	1	4	4	3
Alveolophragmium nitidum							1					.4					.2				.1		.6	.4							4
A ringens										.1												.2	.2	.2							
A. scitulum																								.1							
A subglobosum							.5	.2						.4							.1		.2	.2	.5						
A. wiesneri									.1						.4		.2														
A. sp.							.3											.1				.4		.1		.6					
Ammobaculites sp B						.2			.1	.2		3	2		.3	.2						.3	.5	.6							
Ammodiscus spp					.2		.3					.7		.4			.2					.1		.4						.4	
Ammoscalaria tenuimargo						.7	.3		.1	.2		.4	.4	2		.2						.1			3		.5			1	1
Amphistegina spp	3																	6	5	5			.2				.3	.3			
Angulogerina bella										.1													.3		.3						
A. jamaicensis		.4																			.4	.1									
Anomalinoides mexicana		.1		.1	.2					.5					.1											.3					
Asterigerina carinata																		.4													
Astrononion tumidum					.2				.2								.3							.1							
Bigenerina irregularis	.8																														
B. textularioidea	2																	.1	.1	.7											
Bolivina albatrossi		1	2	.7	3				3	2	2	.4			.1		3				.5	.3	.2	.1	.3	.3					
B. fragilis		.3																.4	.5			.1									
B. goesii	.7	7	1	.2													.2	4	6	5	.2			.1							
B. lanceolata	.8	1	.5	.2	.6				.3	.1	.8						.3	2	4	.8	1	.3				1	.5	.6			
B lowmani	.7	2	2	.9	.2	.4		1	3	2	1	1	2		2	.6	1	2	3	.5	3	2	2	4	.5	4	2	2		.7	.6
B minima	2	3	2	1	4				.4	.6	.7	.7	.7		.1		.2	1	2	1	.4	.2	.2		.3	.3					
B ordinaria		2	4	1	.4			.2	.6	1			.7		.1		.2		.1		1	.6	.6	.4		1					
B. paula	.2			.3					.4						.3		.3				.3		.6		1	.3	.5	.8		.4	
B. pulchella primitiva								.2	.1	.1					.3						.2	.3	.5	.1	.5	.3	.5	.6	.7	.4	3
B pusilla		.1				.2					.7	.4				.2	.3						.2	.6		.3	.3				
B subaenariensis mexicana	.2	.1													.1																.6
B. subspinescens	1	2	4	2	.8				.9	2	1	1	.4		.9	.2		1	2	2	1	1	1	1						.4	
B. translucens		.1								.1												.1				.9			.7		
B. sp.				.1	.6	.2			.9	.7	.4	.7			.7		.9				.7	.1	.3	.5		.3					
Bulimina aculeata			.7	2	4		1		2	2	1	.4			1	2	10				2	.9	.8	.2		.3					
B. alazanensis				.5	15	.2			15	11	2	1	.7		.9	.7	4				7	3	.8	.2	.8	.3	.8		.7	.4	.6
B. spicata		.7	.6	.2	.6		2		2	12					.1	.9	.8			.3	.5	.2	.2	.1							.6
B. striata mexicana		.2		.3		.9	.8		.1					.4	.4	1							.3	.1							
Cancris oblonga	.2	.1								.1								.3		.5	.5					.3				.7	
Cassidulina carinata		1					1	.7	.2	.2			.4			.6															
C. aff. crassa	1	2	2	4	.2				.6	.8			.4		.3	.2	.3	2	.9	2	.9	.3	.5		.8		.5				
C curvata	5	2	5	4						.5	1					.2		3	2	1	.8	.1	.2			.3					.6
C. laevigata																	.3	3	2	2	.3					.3	.8				
C. neocarinata	1	7	7	3	.2					.2	.4						.2	.5	.5	.3	.3									.4	
C. subglobosa & variants	3	4	10	11	7	10	3	3	10	8	7	3	9	2	14	12	9	3	.9	4	15	15	7	11	3	8	3	3	1	4	4
Cassidulinoides tenuis		.1		.1	.2					.3					.1		.5					.1				.3				.4	
Chilostomella oolina										.3						.4					.1										
Cibicides corpulentus	.2			.1	.7				.2	.3					.1		.5				.1	.6									
C. deprimus	1	1		.8	.6										.3			1	.8	2	.4			.1		.6					
C. aff. floridanus	7	.8	2	2	.8				2	1						.2	.8	.5	.8	1	1	.1									
C. kullenbergi						.2	.3		.1			2	1		.3	3						.1	.5	.3		.3		.6	.7	.4	.6
C. mollis																		.4	.1												
C. protuberans	21	9	2	.1													.2	15	17	18	.8	.2	.3								
C. robertsonianus				.7	.9	2	2	2	2	.2	1	.7	3	.4	1	.6	1			.1	2	2	.3	1	1	.6	2	.6	.7	.7	
C. rugosa						.2			.2		.4				.3	.2	.2				.2	.5	.2								
C. umbonatus	.3	2	.5	.7																	.1										
C. wuellerstorfi					.8	4	37	49	.9	.2	.4	5	5	47	2	6	2				1	1	3	1	17	.3	24	27	38	34	35
Cibicidina strattoni	.3				.2													.4													

Table 21. Percentage distribution of benthonic Foraminifera in traverses IX-XI (pt.).

TRAVERSE	IX								X									XI													
STATION	138	140	141	142	144	145	137	108	136	134	131	130	133	129	128	127	126	117	118	116	124	123	122	121	120	113	112	110	111	1	2
DEPTH IN METERS	183	256	320	421	914	2268	3160	3072	1051	950	1920	3200		3180	1737	2150	1317	139	146	155	914	1326	1829	2560	3246	2280	3283	3218	3251	3237	3237
Conorbina orbicularis																			.1	.3											
Cyclammina spp.																						.2	.2			.3	.3			.7	
Dentalina-Nodosaria	.7	.4		.1	.6		.2	.2	.1	.2			.4		.2	.2		.5	1	.1	2	.2	.6	.1			.3		.7	.4	
"Discorbis" bulbosa																					.6	.3	.3			.6					
Eggerella bradyi				.1		1	.5	.2	.4	.2	1	3	2	.8	.3	.2	.3			.1	1	.6	.2	1	2	.6	1	.6	.7	.7	.6
Ehrenbergina spinea		.4								.5								6	3	3	.8										
Elphidium spp.	.2																	.4		.1	.7		.8	.2				.3			
Epistominella decorata					.2	19	3	11			19	6	2	2	12	9	2					1	7	5	15	7	17	14	10	8	7
E. exigua			.2	1	16	.7	.5		4	7	6	2	.4		5	3	1				5	2	4	2	1	2	.3	.3		.4	.6
E. rugosa		.8	11	11	1				2	2	3					.4	.2				5	.3	.2	.6			1	.3			
E. vitrea				.2	.2	.4				.2											.7	.4		.2		.3		.3			
Eponides polius					.2	2	3	3	.7	.2	.4	3	.4	4	.7	.4	2					.7	.6	.3	4		4	4	6	2	4
E. repandus	.2																	.5	.1												
E. tumidulus						3		1			.7	7	5	1	.7	.4	1				.3	1	1	3	3	2	1	3	1	4	1
E. turgidus		.5	1	.2	1	6	.5	6	2	1	11	4	5		3	2	2			.3	3	2	4	5	3	3	.3	2	.7	.4	.6
Pseudoeponides umbonatus	.5	.2	.5	.9		2	5	2	.4	.3	.7		1	2	2	2	.9		.3		.3	.5	1	.8	3	.9	3	3	.7	.4	2
Gaudryina cf. aequa																		.7	.1												
G. (Pseudogaudryina) atlantica	.2	.1	.1															.3		.1											
G. flintii						.4			.9	.2					1	.2	.6			.3	1	1									
Globobulimina affinis & var.							2	3						1										.1	.3		1	.8			
Glomospira charoides				.2		2	1	.7	.4	.1	.7	9	10	.8	2	.4	2				.1	.9	2	2	1	4	.3	.3	3	3	2
G. cf. gordialis								.2			.7	.4	.4	.8	.7	.2	.5						.8	.4	.8	2			.7		
Gypsina vesicularis																		.3	.1	.1											
Gyroidina neosoldanii	.2	.1	.4	.4		.2	1								.3	.6					.2		.6	.1	.5	.3	.2			.7	.6
G. orbicularis		.3	.4	.1	2	.4	2	.5	3	1	2	.7	.4	.8	2	3	3				.7	2	2	.3		2	.3	.3			
Gyroidinoides soldanii altiformis	.2	.5		1	.2	.4		1	.5	.3	.4				.1		.3				.5							.6	.7		
Haplophragmoides bradyi				.1		.6		.7	.1			2	2	.4		.2	.3					1	.5	.2	1	.3	1	.8	.7	1	.6
Höglundina elegans	.3	.8	.2	1	.7	12	6		2	2	5	3	10	4	3	25	7	.1	.6	.8	1	4	3	5		10	9	3	3	5	3
Karreriella bradyi	.3	.6		.3	.4		.3		.5								.2	.5	.4	.4		.2	.2	.2							
Lagena spp. & related forms	1	1	2	4	4	8	2	1	6	3	6	3	9	2	8	2	4	.8	5	.1	4	8	7	10	4	4	4	5	3	4	3
Laticarinina pauperata		.1	.4	1	.9	2	2	.2	1	1	2	.4	1		1	.9	2				1	2	.9	1	.3	.3					
Lenticulina peregrina		.3	.5	.2	1				1	.8	.7				.6		.8		.3		.9	.6	.2								
Liebusella spp.	.8	.2																.3	1	.8											
Loxostomum abruptum		.3	.7	.4		2			.5	.7	1				.7	.7					.6	.3	.2	.8		.3		.8			
Miliolidae	2	3	.8	.9				.2		.1		.4	1		2	.9	1	4	4	1	.8	6	4	3	.5	2	1	.3		.4	
Nodobaculariella cassis	.5																	.5	.5	.6											
Nodosaria hispida				.5																	.2										
Nonion formosum	.3	.3			.4													.7	.3												
N. pompilioides						.4	3	3				.7	.7	4										.6	3	.3	4	8	6	3	6
Nonionella atlantica																							.2								
N. opima																					.2					.3					
Nummoloculina irregularis			.4	.1											2	.7	.2				3	5	5	1		.9					
Osangularia cultur					4		.5		2	3	1	.4	.4	.4	2	2	2				2	1	2	.6	.5	.6	1	.3		1	.6
Peneroplidae																		.9		.1											
Planorbulina mediterranensis	.3																	1	2	1		.2					.3				
Planulina ariminensis	.2	.7	2	4					.2	.5										.3	.5		.2	.2							
P. exorna	.5	.2																.4													
P. foveolata	3	5																2	3	2											
Plectina apicularis							1	.2				2	2	3	.1		.6					.3	.7		2		2	1	2	2	1
Proteonina difflugiformis								.2				3					.3							2	1	.6					
Pseudoclavulina mexicana	.2																	.4	.5	.4											
P. aff. novangliae	.3					.2																									
Pseudoglandulina comatula		.2		.1						.1								.3	.3	.4							.3				
Pullenia bulloides		.2		.6	.6	.4	.3	.5	.5	.2	1	.4		.4	2	1	1			.1	1	2	2	.6	1	.6	.3	.3	.7	1	.6
P. quinqueloba	.3	.2	.6	.4	1	.7	.8	1	1	.5	2		1	1	2	.7	2	2	.9	.9	.8	1	2	1	.8	.6	1	1	.7		1
P. sp.						.4		.2	.2			.4		.4	.4	.6						.5	.2	1	1	1		.8	.7	1	
Pyrgo murrhina				.5	1	3	2	.7	1	.9	1	.7	4	2	.4	1	2				.3	.6	.2	2	.5	2	2	.6	1	.4	3
P. cf. nasutus	.5	.2	.4															.3	1	.7							.3				
Quinqueloculina compta																				.1											
Q. horrida	.7	.3																													
Q. lamarckiana	.7														.1	.4		1	.4	.5											
Q. cf. polygona	.3																	.1													
Q. venusta						.4	.5					.7	1		.3								.8	.8		.6		.3		.4	
Q. sp.					.7	2	1		.8	.1		2	1	.4	.4	4	.9				.6	1	3	1		.3	.5	.3	1	1	.6
Rectobolivina advena		.1																						.2							

Table 22. Percentage distribution of benthonic Foraminifera in traverses IX-XI (pt.).

TRAVERSE	IX								X									XI													
STATION	138	140	141	142	144	145	137	108	136	134	131	130	133	129	128	127	126	117	118	116	124	123	122	121	120	113	112	110	111	1	2
DEPTH IN METERS	183	256	320	421	914	2268	3160	3072	1051	950	1920	3200		3180	1737	2150	1317	139	146	155	914	1326	1829	2560	3246	2280	3283	3218	3251	3237	3237
Rectobolivina dimorpha				.1																		.1									
Reophax bilocularis				.3								2										.5		.3		.3					
R. distans delicatulus						.4	.5	.2				3	.4	4	.3							.2	.5	1	5	2	1	.6	1	1	3
R. guttifera																										.3					
R. hispidulus									.2	.3		2			.4		.2				.1	1	.2	2	1	.6	.3			1	
R. irregularis	4	.5																.4	.3												
R. scorpiurus												.7																	1		
R. sp.													.4																		
Reussella atlantica	.7														.1			2	.9	1	.8										
Robertina bradyi	.2	.1	.2	.1	.9				.8	.7					2	.7	.6				.7	1	2	.4		2					
Robulus spp	2	2	2	3	.4				.1	.2	.4					.4	.2	3	3	6	.3	.4					.5				
Rosalina bertheloti	.8	1							.2									.5	.9	.5	1										
R. cf. concinna		.3							.6	.3							.3	2	.4	.3	2	.3	.5	.7						.4	
R. floridana	.2												.4					.1	.1	.1											
R. floridensis	.7																	.5	.3	.3											
R. parkerae		.2		.2		.7		1	.1				.4	.4	.6		.2		.4		1	.4	.5	.6		.9					
R. suezensis	.2	.5	.6	.3	.4																							.3			
"Rotalia" translucens		2	12	8	3	.4	.5		4	6	5	1	.4	.8	3	.9	4				3	3	1	1	.5		.8	.3			.6
Rotamorphina laevigata	.2	1		.2	.4				.8	1	1	.7	1		.4	.4	.2	.4	.4	.1	.4	.4	.5	.4		2	.3	.3			.6
Saccamminidae & related forms																										.3					
Seabrookia earlandi			.2						.4	.1		.4			.1		.9	.1	.1	.1	.1	1	.5	.9		2		.3			
Sigmoilina distorta		.4													.6			.8		.8	.4										
S. schlumbergeri		.2	.4			.2	.5	2	.4	.3	.4			1	.4	.9	1				.1	.2	.6	.2	1					.7	
S. tenuis	1	.8	.6						.7	.2		.4					.2	1	.9		.7	.5								.4	
S. sp.	.7	.7																.3		.3											
Siphonina bradyana	.2	.7	.6	.4						.1								1	.8	1											
S. pulchra	.5	1	.1	.4														1	.4	.4											
Siphotextularia curta					.2				.3	.3					.1	.2	.5				.1	.4	.7	.3							
S. rolshauseni												4			.1		.2							.1	1		.3	.8		.4	1
Sphaeroidina bulloides	.3	.7	.6	2	.6	.2			1		.4						.5			.1	.9	.5	.6			.6	.8				
S. compacta									.2						.3		.3		.1			.5	.2			.3					
Spirillina vivipara					.2				.1									.3	.1												
Spiroloculina soldanii	.3	.1	.1						.1										.1	.5											
Spiroplectammina floridana	.3																	.7	.5	.4											
Stetsonia minuta		.1							.5	.3			.4				.2	.3			.1			.1		.6		.3	.7		
Textularia candeiana	3	2	.4															1	1	1											
T. conica	1	.2																1	.9	2											
T. foliacea occidentalis	3	1																1	.8	1											
T. mayori	.2	.2																.3	.1												
Textulariella spp	2	.4	.1															1	1	3											
Tolypammina schaudinni						.9						4	2	2	1		.6					.2	.5	3		2				.4	
Trifarina bradyi	.5	.5	6	8	3				3	2	2	.4	1		.4	.2	.2	.3	.4	.5	2	.2		.2		.9				.4	
Triloculina cf brevidentata	.5	.5														.2		.8	.1	1											
T. tricarinata					.2				.2			.7			1		.2					1	.3	.9		.6			.7		
Trochammina globulosa						.4	.3		.1			1	2		.3		.8					.3	.2	1		3					
T. cf. japonica												.4			.3		.3						.2	.4		.3					
T. quadriloba																									1						
T. squamata & related spp									.1															.1							
T. cf. tasmanica						.2						2										.2		.9		.6				.4	
Uvigerina auberiana		.2	3	1		.7	3	.2	.7	.8	.4				.4	1	.5				.2	.2	.5	.6		.3			2	.7	.6
U. flintii	3	4	.4	.2														2	3	6											
U. hispido-costata		.1	.6	1					.3	2																					
U. laevis	1	2		.2					.1	.3	.7		.4		.1		.2	1	1	.7	.8		.8	.1		.3	.5				
U. parvula	3	6	.2															3	5	4											
U. peregrina				.3	12	.9	2		5	8	.7				.9	.9	6				.8	2	.3	.3							
Valvulineria mexicana								1																			.3	.6			.6
V. minuta		.4	.1	1	.9	.2			.2	.7	.7						.6		.4		.5	.4	.2	.3	.6	.3					
Virgulina advena						.9		.2					1			.4								.1		.3					1
V. complanata		.1	.6	.2		.4		.2		.5			1				.2	.1		.1	.1	.3	.3								.6
V. mexicana		.1										.4			.1	.2								.1							
V. pontoni																						.1				.3					
V. punctata										.2								.1	.1		.1	.2	.2	.4		.3					
V. tessellata																					.1										
Miscellaneous spp.	5	4	4	6	.1	5	4	1	3	3	3	4	3	2	5	2	4	4	4	8	3	7	9	8	7	7	3	7	5	5	.6

Table 23. Percentage distribution of benthonic Foraminifera in traverses IX XI (pt.).

TRAVERSE	VII																		
STATION	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	107
DEPTH IN METERS	22	31	46	49	86	146	183	186	237	274	274	320	347	457	585	732	878	2999	3017
TOTAL PLANKTONIC POPULATION	12	8	34	450	150	2 300	27 100	12 800	19 500	14 000	14 800	20 700	60 900	200 000	56 800	16 000	34 600	47 300	40 400
Candeina nitida																.4	.2	.3	.3
Globigerina bulloides	17			4	18	5	16	17	19	13	18	13	10	6	9	12	14	14	16
G. digitata											1		.1	.1	.2	.4		.1	
G. eggeri			24	4	19	23	9	11	7	9	7	9	11	8	8	11	9	8	6
G. inflata						1	2	2	3	1	1	2	1	.9	.7			.1	
G. pachyderma																	.2	.7	
G. sp.						2	4	2	3	2	3	.8	3	4	2	1	1		1
Globigerinella aequilateralis					1	3	.7	1	2	3	4	3	3	3	5	5	2	5	6
Globigerinita glutinata				18	4	3	9	10	11	4	9	2	9	9	6	4	5	3	5
Globigerinoides conglobata					8	1	.5			.7	.4	.9	.3	.2	.3	.4	.4	.1	.5
G. rubra	50	100	64	52	27	28	36	39	34	35	34	33	32	40	40	33	33	34	35
G. sacculifera	33				3	5	3	2	3	5	4	13	10	10	13	9	13	12	10
Globorotalia hirsuta																			.1
G. menardii					10	8	3	3	2	5	5	6	5	4	4	7	6	7	6
G. punctulata				4		.8	3	1	2	2	2	3	3	3	2	1	2	2	.6
G. scitula						1	4	3	6	2	2	2	1	1	2	1	2	.5	.6
G. truncatulinoides			12	18	7	5	5	3	3	8	5	7	4	3	3	5	4	4	3
G. tumida					3	1	1	1	.8	1	.2	.9	.2	1	1	1	2	.7	.5
Hastigerina pelagica																			.1
Orbulina universa						1	.2	.7	.2	2	.1	1	.8	3	2	4	2	3	4
Pulleniatina obliquiloculata						12	4	4	4	7	3	3	6	4	2	4	4	5	4
Sphaeroidinella dehiscens						.1		.2				.2				.2	.2		.1

Table 24. Percentage distribution of planktonic Foraminifera in traverse VII.

TRAVERSE	I											II																					
STATION	211	210	209	208	207	206	205	204	202	203	201	16	17	18	19	20	21	22	23	15	24	14	13	12	11	10	9	8	7	6	5	4	3
DEPTH IN METERS	51	786	786	73	82	79	82	91	128	201	430	33	58	88	106	113	142	168	208	298	314	471	631	732	914	1298	1372	1417	1875	2468	2788	2972	3017
TOTAL BENTHONIC POPULATION	30	229	14	101	30	11	17	20	22	9	8	31	115	20	1	6	12	22	6	3	22	0	6	1	3	1	2	5	1	1	12	0	0
Alveolophragmium scitulum											2																						
A. sp.					1			1																									
Ammobaculites sp. A										1						1	2	2															
Ammoscalaria pseudospiralis														1																			
Bolivina albatrossi																							1					1					
B. barbata		2		19														3															
B. ordinaria																		2															
B. striatula spinata				6																													
Bulimina marginata																		3			1												
B. striata mexicana																				1	1												
Buliminella cf. hassendorfensis		1		50								1																					
Chilostomella oclina																							2								1		
Cibicides aff. floridanus																												1					
C. wuellerstorfi																											1						
Eponides regularis																		2															
Globobulimina affinis & var.																								1	1								
Goesella mississippiensis		2	4	8	2	1	2	4	7	2				3		4	5	4	1												3		
Gyroidina orbicularis																										1	1	1					
Hormosina sp.											2																						
Miliolidae																														1			
Nonionella opima	4				2																2												
Nouria polymorphinoides																															5		
N. sp.	24	114	3	5	9	2	14	2				25	64	10	1						1												
Osangularia cultur																							1										
Proteonina atlantica																															1		
P. difflugiformis				1	3	6		5	4	5	1			2		1	1	2							1								
Reophax gracilis		26	2								1		1																				
R. hispidulus					2			1	4					1			1	2	1				1					1			2		
R. scorpiurus				1	2			3	2								1	1	4	1													
R. spp																					6												
Robulus spp																												1					
"Rotalia" beccarii variants		33					1					5	8																				
Saccamminidae & related forms																	2																
Sphaeroidina bulloides																									1				1				
Textularia earlandi	2	50	3										42	3							1												
Trochammina cf. japonica											1																						
T. quadriloba					9	2		4	2	1	1																						
T. cf. tasmanica			2															1															
T. spp. (juvenile)																					7												
Valvulineria mexicana																					2												
Virgulina mexicana																				1													
V. pontoni				10																	1												
V. tessellata																							1										
Miscellaneous spp.		1		1					3																								

Table 25. Distribution of living benthonic Foraminifera in traverses I and II (in numbers of specimens).

TRAVERSE	III													IV													V										
STATION	25	26	27	28	29	30	31	32	33	34	35	36	37	225	224	222	221	220	219	218	217	216	215	214	213	212	78	76	75	74	99	100	101	102	103	104	105
DEPTH IN METERS	22	53	77	106	155	205	373	400	1024	1262	1481	1719	2388	20	20	33	35	37	38	42	40	42	47	49	55	62	71	99	146	204	238	530	914	1097	1822	2213	1417
TOTAL BENTHONIC POPULATION	103	14	30	78	96	70	12	11	17	27	19	5	1	■	50	28	61	53	194	87	38	33	287	232	37	62	46	35	52	34	19	11	24	10	■	5	1
Ammoscalaria pseudospiralis																	3	1		2	3		5		13	1											
Angulogerina bella																	1		2			5	16	2													
Anomalinoides mexicana																																	1				
Bigenerina irregularis																			1			1	4														
Bolivina albatrossi						1		1	5	1																				2							
B. barbata				21	45	10																															
B. lowmani									1											1									1	1							
B. ordinaria						11																															
B. striatula spinata		1	7	3	1																	2	32	46					1								
B. subaenariensis mexicana				32	35																							2	3	2							
Bulimina aculeata								2			2																					1			1		
B. marginata					2	6																	1						2		1						
B. spicata																														1							
B. striata mexicana																															2	1	1			1	
Buliminella cf. bossendorfensis	8	8	8	10														2	1			2	5														
Cancris oblonga																	1	2	3	2			1				8	3	2								
Cassidulina carinata							1																														
C. curvata																													1	1							
C. neocarinata																													2			1					
C. subglobosa & variants																				2									3	1							
Chilostomella oolina									6	4																			4	5	2	6	12	2		1	
Cibicides aff. floridanus																													7								
Cibicidina strattoni																8	8	5	3			2	3														
Dentalina - Nodosaria																				1			2														
Elphidium discoidale																	1		3																		
E. gunteri																1							2	1													
E. poeyanum																1																					
Epistominella vitrea		4	2	2	2					1				2			1		2	1		1	5	1									1				
Eponides antillarum																	3																				
E. regularis						35	3																														
Pseudoeponides umbonatus																												1									
Globobulimina affinis & var.									2	11	5	1																					1				
Goesella mississippiensis			1	2	3																		14		9	9	1	3									
Gyroidina orbicularis												1																									
Hormosina sp.						1	1		1	1																											
Lagena spp. & related forms				1	1					1		1										1															
Lenticulina peregrina																																					1
Miliolidae																	1		2			1															
Nonionella atlantica					1	1								1		5	1			2		3	4				1										
N. opima	3		2		1					1				1	44	4	22	17	119	40	1	5	104	153			26	16	4	3	1						
Nouria polymorphinoides														1	1	5		7	41	31	14	1	13	10			6	1									
N. sp.	7																								10	8											
Planulina foveolata																													1	3							
Proteonina atlantica																	15	15	2	1	19	7	70		2		1		2		1						
P. difflugiformis						1	1	2																										1			
Pullenia bulloides								1																						1					1		
P. quinqueloba																																	6	1			
Pyrgo cf. nasutus																			3										3								
Quinqueloculina compta																	1	1				1															
Q. lamarckiana																		1																			
Reophax gracilis																								6													
R. hispidulus								1		1	1																		4	2	2					1	
R. irregularis																											2										
R. scorpiurus																							1														
R. spp.																													2			1					
Reussella atlantica																			1					1													
Robulus spp				1																											2						
Rosalina bertheloti																	1																				
R. cf. concinna															5	2																					
R. floridana																		1												2							
"Rotalia" beccarii variants	3	1															1		2	1			1														
Rotamorphina laevigata								1		1																			1					1	1	1	
Sphaeroidina bulloides										1																			1		1		1				
Textularia earlandi	11		1			1																			3	44											
T. mayori																1	1		1	1																	
Trochammina advena						1																															
T. spp. (juvenile)	71																																				
Uvigerina laevis																												1	1	1							
U. parvula																								1							5						
U. peregrina								2	1				1																	1			1		2		
Valvulineria mexicana							4																														
Virgulina mexicana								1																													
V. pontoni			9	3	4											1			2			1	3	11													
V. punctata																		1	3	2							1	5			1						
V. tessellata										4	11																							5			
Miscellaneous spp.				3	1	2	2		1		2								3		1		1					3	7	8	1	1				1	

Table 26. Distribution of living benthonic Foraminifera in traverses III-V (in numbers of specimens).

TRAVERSE						VI																					VII											
STATION	197	198	200	196	199	59	58	57	56	54	53	52	51	49	48	47	46	45	44	43	42	41	40	39	38	106	179	181	182	183	184	185	186	187	188	189	190	191
DEPTH IN METERS	549	549	600	713	735	91		106	113	128	139	146	155	183	223	446	555	631	650	677	823	860	960	1144	1573	2697	146	186	237	274	274	320	347	457	585	732	878	2999
TOTAL BENTHONIC POPULATION	11	16	7	11	12	15	4	4	4	15	12	1	5	3	5	6	11	5	1	9	9	5	2	1	0	1	5	5	6	4	4	6	0	4	0	5	2	6
Ammoscalaria tenuimargo																																						1
Bolivina albatrossi					1											2																						
B. lanceolata						3				1																												
B minima											1																											
B striatula spinata									1	1																	5											
B subaenariensis mexicana																												1				1						
Bulimina aculeata			1	1	1																		1	1														
B alazanensis					1																																	
B. spicata				2																																		
B. striata mexicana		1			5																																	
Cancris oblonga						1				1																			1									
Cassidulina neocarinata																					1																	
C. subglobosa & variants						1														1																1		
Chilostomella oolina	1	7		2										1		1	7	3		1												1						
Cibicides corpulentus											2																											
C aff. floridanus																				1	1	1														1		
C mollis						1																																
C robertsonianus																																						1
C rugosa			1																																			
Dentalina - Nodosaria	1												1																		1			1				
Eggerella bradyi	1																																					
Epistominella decorata																					1																	
E exigua	1																1																					
E rugosa					1																																	
Eponides regularis													1																									
E turgidus	1																																					
Pseudoeponides umbonatus																				1																		
Gyroidina orbicularis																													1									
Hoglundina elegans						1		2				1																										
Karreriella bradyi																			1																			
Lagena spp & related forms					1						1										1		1															
Miliolidae											1																	1										
Nonionella atlantica						1																																
Osangularia cultur				1																1	1																	
Planulina exorna							1																															
Proteonina atlantica						1			1	2																		1		1								
P difflugiformis	1		1																	2																		
Pullenia bulloides															1	1																						
P quinqueloba						1																																
Pyrgo murrhina																										1												
P cf nasutus										1																												
Reophax bilocularis										1																						1						
R guttifera																														1								
R. hispidulus	1	1												2														1	1	1	1	1						1
R. irregularis						1																																
R. scorpiurus	1	2													1							2																
R spp											1				1		2												1			1						
Robulus spp						1		1	1	2																					1							
Rosalina floridensis							1																															
"Rotalia" translucens	1																																					
Rotamorphina laevigata															1																							
Siphonina bradyana		1													1																							
S. pulchra									1	4	2																	1	1					1				
Sphaeroidina bulloides	1	1	2	1	1						1							2				1																
Trifarina bradyi							1													1																		
Trochammina globulosa																				1																		
Uvigerina flintii											1																											
U. hispido-costata					1																											1		2				
U peregrina			2													2					2								1		1					2	1	
Valvulineria minuta																					1	1																
Virgulina tessellata	1	1		3																																		
Miscellaneous spp		2		1		3	1	1		2	2		3				1				1									1						1	1	3

Table 27. Distribution of living benthonic Foraminifera in traverses VI and VII (in numbers of specimens).

TRAVERSE	VIII								IX							X								XI										
STATION	154	153	152	151	150	149	148	146	140	141	142	144	145	137	108	136	134	131	130	129	128	127	126	124	123	122	121	120	113	112	110	111	1	2
DEPTH IN METERS	117	146	183	366	585	914	1730	3164	256	320	421	914	2268	3160	3072	1051	950	1920	3200	3180	1737	2150	1317	914	1326	1829	2560	3246	2280	3283	3218	3251	3237	3237
TOTAL BENTHONIC POPULATION	12	40	13	10	6	2	1	1	3	6	2	6	1	0	0	4	5	1	2	0	13	1	14	11	6	6	7	0	3	0	0	0	0	0
Alveolophragmium ringens																											1							
A. subglobosum						1																												
A. wiesneri		1																																
Ammoscalaria tenuimargo				1																														
Bolivina goësii		1																																
Bulimina aculeata																							3		1									
Cancris oblonga	1	1																																
Cassidulina subglobosa & vars												1				2					1		2	1										
Chilostomella oolina				2																														
Cibicides aff. floridanus					1																													
C. robertsonianus																					1					1								
C. umbonatus	1																																	
C. wuellerstorfi																									1									
Dentalina - Nodosaria																								2										
Epistominella decorata																										2			1					
E. exigua																					1													
E rugosa											1																							
Eponides polius																	1																	
E. turgidus																											1							
Goudryina (Pseudogaud.) atlantica			1																															
Gyroidina orbicularis																1	1				1					1								
Höglundina elegans		2														1			1		1	1	1	1		1	1							
Lagena spp. & related forms			1									1																						
Laticarina pauperata																									1									
Marginulina marginulinoides	1																																	
Miliolidae	2								1																		1							
Osangularia cultur												2									1		2	1										
Proteonina atlantica	1	3																																
Pullenia bulloides					1												1																	
P. quinqueloba	2								1												1		1			1								
Pyrgo murrhina																											1							
P. cf. nasutus		2		1																														
Reophax hispidulus		2		1	2	1	1	1		1									1		1		1											
R. irregularis	1	2																																
R. scorpiurus																							1											
R spp	2	1		2																							1							
Robulus spp.			1	3					1	1																								
"Rotalia" translucens																									1									
Rotamorphina laevigata											1																							
Seabrookia earlandi										2																								
Siphonina pulchra		18	8																															
Siphotextularia curta																								1										
S. rolshauseni													1																					
Sphaeroidina bulloides	1		1									1					1				2		2	1	1									
Textulariella spp										1																								
Trifarina bradyi										1																								
Trochammina squamata & rel. spp.																								1										
T. spp. (juvenile)																								1			1							
Uvigerina flintii		5	1																															
U. peregrina					2							1						1					1		1									
Valvulineria minuta																													2					
Miscellaneous spp		2															1				3			2										

Table 28. Distribution of living benthonic Foraminifera in traverses VIII-XI (in numbers of specimens).

TRAVERSE	II						III		IV				
STATION	9	8	6	5	4	3	34	37	222	221	220	218	215
DEPTH IN METERS	1372	1417	2468	2788	2972	3017	1262	2388	33	35	37	42	47
TOTAL PLANKTONIC POPULATION	7	5	2	11	5	2	5	6	2	2	1	2	1
Globigerina bulloides	1			2			1						
G. eggeri				1			2	1					
G. (juvenile)	4	4	1	2	5		2	5		1		2	1
Globigerinella aequilateralis						1							
Globigerinita glutinata				2									
Globigerinoides rubra						1			2	1	1		
G. sacculifera	1												
Globorotalia menardii				2									
G. punctulata	1			1									
G. truncatulinoides													
Orbulina universa			1										
Pulleniatina obliquiloculata		1		1									

TRAVERSE	V										VI													
STATION	78	76	75	74	99	100	103	104	105	198	59	57	54	53	49	48	47	46	44	43	42	39	38	106
DEPTH IN METERS	71	99	146	204	238	530	1822	2213	1417	549	91	106	128	139	183	223	446	555	650	677	823	1144	1573	2697
TOTAL PLANKTONIC POPULATION	3	2	3	6	2	3	2	1	4	1	2	1	1	2	2	2	2	1	5	2	3	2	3	1
Globigerina bulloides																								
G. eggeri											1				1	1		1						
G. (juvenile)	1	1	3	3	1	3		1	4				1	2					5	2	3	2	2	1
Globigerinella aequilateralis				1													1						1	
Globigerinita glutinata																								
Globigerinoides rubra				1	1										1		1							
G. sacculifera	1																							
Globorotalia menardii	1									1	1													
G. punctulata																								
G. truncatulinoides							2																	
Orbulina universa				1																				
Pulleniatina obliquiloculata		1										1				1								

Table 29. Distribution of living planktonic Foraminifera in traverses II-VI (in numbers of specimens).

TRAVERSE	VII										
STATION	181	182	183	184	185	186	187	188	189	190	191
DEPTH IN METERS	186	237	274	274	320	347	457	585	732	878	2999
TOTAL PLANKTONIC POPULATION	3	6	1	1	3	1	2	2	2	8	3
Candeina nitida											
Globigerina bulloides											
G. digitata											
G. eggeri	1										
G. (juvenile)		4	1		2				2	3	2
Globigerinella aequilateralis											
Globigerinita glutinata	1						1			1	1
Globigerinoides rubra										1	
G. sacculifera											
Globorotalia menardii		1								2	
G. punctulata											
G. scitula										1	
G. truncatulinoides					1		1	1			
G. tumida											
G. (juvenile)											
Orbulina universa											
Pulleniatina obliquiloculata	1	1		1		1		1			

TRAVERSE	VIII							
STATION	154	153	152	151	150	149	148	146
DEPTH IN METERS	117	146	183	366	585	914	1730	3164
TOTAL PLANKTONIC POPULATION	5	9	2	9	5	29	4	3
Candeina nitida					1			
Globigerina bulloides						2		
G. digitata								
G. eggeri						3		
G. (juvenile)		6		4		3	1	
Globigerinella aequilateralis	1	1			1	7		
Globigerinita glutinata				1			1	
Globigerinoides rubra				1	1	4		
G. sacculifera						1		
Globorotalia menardii	2		1		1	1		
G. punctulata								
G. scitula								
G. truncatulinoides		1		2		5		2
G. tumida					1			
G. (juvenile)								
Orbulina universa	1	1				1		1
Pulleniatina obliquiloculata	1		1	1		2	2	

TRAVERSE	IX						
STATION	140	141	142	144	145	137	108
DEPTH IN METERS	256	320	421	914	2268	3160	3072
TOTAL PLANKTONIC POPULATION	9	11	3	3	6	1	4
Candeina nitida							
Globigerina bulloides					1		
G. digitata							
G. eggeri	1						2
G. (juvenile)	5	5	2	2	3		
Globigerinella aequilateralis				1			1
Globigerinita glutinata		2			1		
Globigerinoides rubra	1						1
G. sacculifera							
Globorotalia menardii		1	1		1		
G. punctulata							
G. scitula							
G. truncatulinoides	2						
G. tumida							
G. (juvenile)							
Orbulina universa		1					
Pulleniatina obliquiloculata		2				1	

TRAVERSE	X							
STATION	136	134	131	130	129	128	127	126
DEPTH IN METERS	1051	950	1920	3200	3180	1737	2150	1317
TOTAL PLANKTONIC POPULATION	74	21	5	4	7	32	12	32
Candeina nitida								
Globigerina bulloides	1						2	2
G. digitata		1						
G. eggeri	2					6	2	1
G. (juvenile)	57	11	4	1	2	6	5	16
Globigerinella aequilateralis	4	1		1		10		3
Globigerinita glutinata				1	1		1	3
Globigerinoides rubra	2	2		1				2
G. sacculifera	1						1	1
Globorotalia menardii	5	1				6	1	2
G. punctulata	1				1			1
G. scitula		1						
G. truncatulinoides	1	1				2		1
G. tumida								
G. (juvenile)			1					
Orbulina universa		2				1		
Pulleniatina obliquiloculata		1			3	1		

TRAVERSE	XI							
STATION	124	123	122	121	113	110	111	1
DEPTH IN METERS	914	1326	1829	2560	2280	3218	3251	3237
TOTAL PLANKTONIC POPULATION	32	6	21	7	24	2	3	3
Candeina nitida								
Globigerina bulloides	2			3		1		
G. digitata								
G. eggeri	4		4					
G. (juvenile)	4		7		8		1	3
Globigerinella aequilateralis	4	3	2	2	4		2	
Globigerinita glutinata		1						
Globigerinoides rubra	1		1	1				
G. sacculifera	1				1			
Globorotalia menardii	12		4		4			
G. punctulata		1		1	1			
G. scitula	2				2			
G. truncatulinoides	1	1			2			
G. tumida	1							
G. (juvenile)								
Orbulina universa						1		
Pulleniatina obliquiloculata			3		2			

Table 30. Distribution of living planktonic Foraminifera in traverses VII-XI (in numbers of specimens).

PLATES

PLATE 1

Fig. 1. *Proteonina atlantica* Cushman. X 42. Sta. 222.

Fig. 2. *Proteonina difflugiformis* (H. B. Brady). X 62. Sta. 208.

Fig. 3. *Reophax bilocularis* Flint. X 39 Sta. 187.

Fig. 4. *Reophax distans delicatulus* Cushman. X 42. Sta. 37.

Fig. 5. *Reophax guttifera* H. B. Brady. X 42. Sta. 15.

Figs. 6, 7. *Reophax hispidulus* Cushman. X 42. (6) Sta. 191; (7) Sta. 121.

Fig. 8. *Hormosina* sp. X 70. Sta. 13.

Figs. 9, 10. *Reophax irregularis* n. sp. Sta. 59. (9) Holotype, X 33; (10) Paratype, X 39.

Fig. 11. *Reophax scorpiurus* Montfort. X 39. Sta. 24.

Fig. 12. *Reophax* sp. X 42. Sta. 23.

Fig. 13. *Glomospira* cf. *gordialis* (Jones and Parker). X 42. Sta. 24.

Fig. 14. *Glomospira charoides* (Jones and Parker). X 62. Sta. 36.

Fig. 15. *Tolypammina schaudinni* Rhumbler. X 62. Sta. 121.

Fig. 16. *Haplophragmoides bradyi* (Robertson). X 70. Sta. 36.

Fig. 17. *Alveolophragmium nitidum* (Goës). X 39. Sta. 8.

Fig. 18. *Adercotryma glomeratum* (H. B. Brady). X 42. Sta. 8.

Fig. 19. *Alveolophragmium ringens* (H. B. Brady). X 42. Sta. 5.

Figs. 20, 21. *Alveolophragmium scitulum* (H. B. Brady). X 42. (20) Sta. 8; (21) Sta. 5.

Fig. 22. *Alveolophragmium* sp. X 62. Sta. 35.

Fig. 23. *Alveolophragmium wiesneri* (Parr). X 64. Sta. 33.

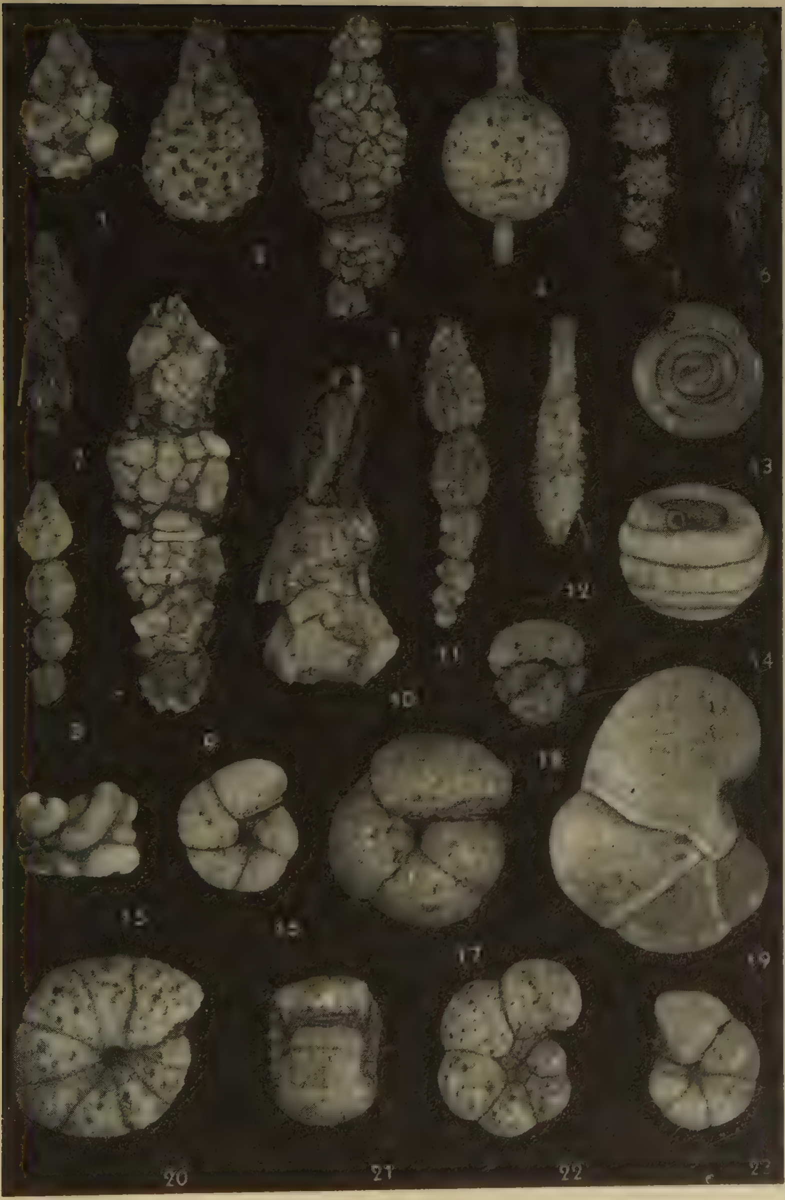
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Plate 1

PLATE 2

Figs. 1, 2. *Alveolophragmium subglobosum* (G. O. Sars). X 33. (1) Sta. 4; (2) Sta. 191.

Figs. 3, 4. *Ammoscalaria pseudospiralis* (Williamson). X 42. (3) Sta. 225; (4) Sta. 208.

Fig. 5. *Ammoscalaria tenuimargo* (H. B. Brady). X 42. Sta. 107.

Fig. 6. *Ammobaculites* sp. B. X 70. Sta. 104.

Figs. 7, 8. *Ammobaculites* sp. A. (7) X 42. Sta. 203; (8) X 31. Sta. 202.

Fig. 9. *Spiroplectammina floridana* (Cushman). X 42. Sta. 156.

Fig. 10. *Textularia foliacea occidentalis* Cushman. X 39. Sta. 116.

Fig. 11. *Textularia mayori* Cushman. X 33. Sta. 92.

Fig. 12. *Textularia earlandi* Parker. X 70. Sta. 30.

Fig. 13. *Textularia conica* d'Orbigny. X 39. Sta. 117.

Fig. 14. *Siphotextularia rolshauseni* Phleger and Parker. X 62. Sta. 191.

Fig. 15. *Siphotextularia curta* (Cushman). X 42. Sta. 121.

Figs. 16, 17. *Textularia candeiana* d'Orbigny. (16) X 42. Sta. 116; (17) X 31. Sta. 85.

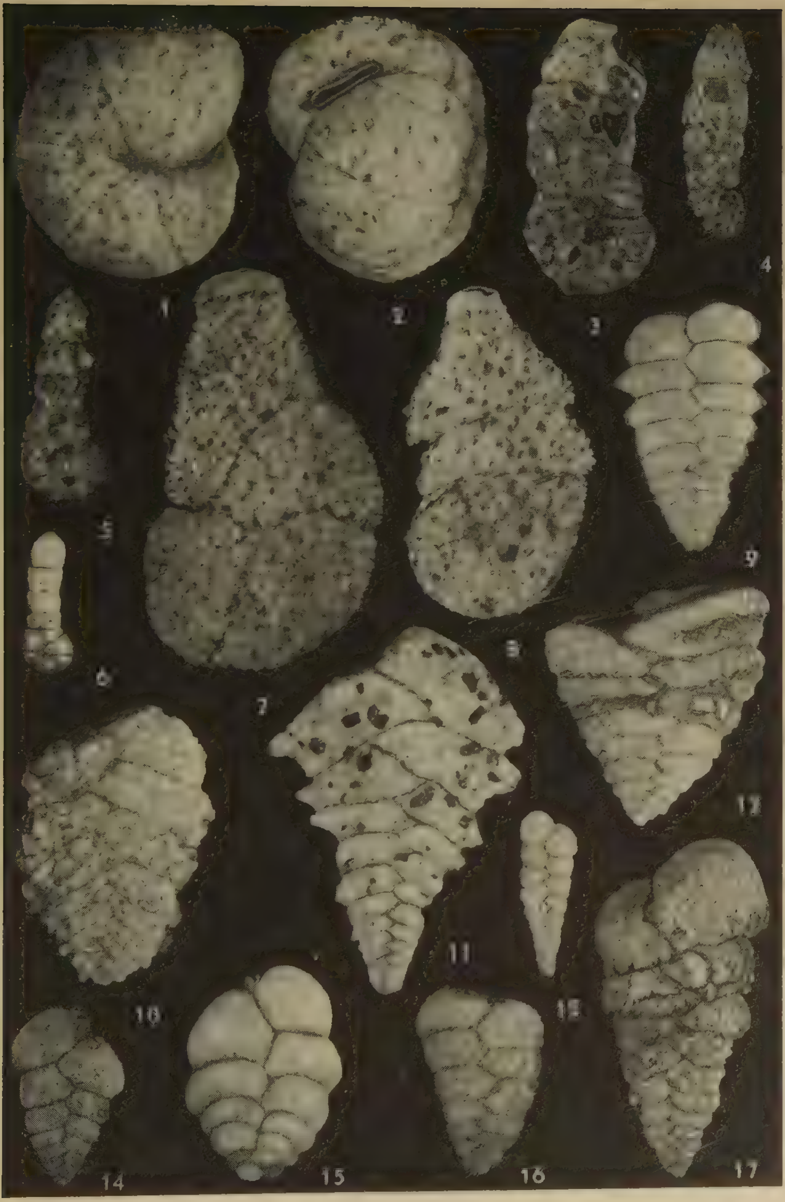
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Plate 2

PLATE 3

Figs. 1, 2, 3. *Bigenerina irregularis* Phleger and Parker. X 39. (1, 2) Side views; (3) Edge view. Sta. 164.

Figs. 4, 5. *Bigenerina textularioidea* (Goës). (4) X 22. Side view; (5) X 42. Edge view. Sta. 90.

Fig. 6. *Gaudryina flintii* Cushman. X 24. Sta. 128.

Fig. 7. *Gaudryina* (*Pseudogaudryina*) *atlantica* (Bailey). X 22. Sta. 181.

Fig. 8. *Pseudoclavulina mexicana* (Cushman). X 24. Sta. 181.

Figs. 9, 10. *Pseudoclavulina* aff. *novangliae* Cushman. X 24. Sta. 52.

Fig. 11. *Karreriella bradyi* (Cushman). X 47. Sta. 116.

Fig. 12. *Gaudryina* cf. *aequa* Cushman. X 62. Sta. 77.

Figs. 13, 14, 19. *Goësella mississippiensis* n. sp. (13, 14) X 62. Paratypes; (19) X 42. Holotype. Sta. 28

Figs. 15, 16. *Gaudryina* cf. *minuta* Earland. X 70. (15) Sta. 12. (16) Sta. 11.

Fig. 17. *Eggerella bradyi* (Cushman) X 42. Sta. 191.

Fig. 18. *Plectina apicularis* (Cushman). X 42. Sta. 191.

Figs. 20, 21. *Quinqueloculina compta* Cushman. X 42. Sta. 214.

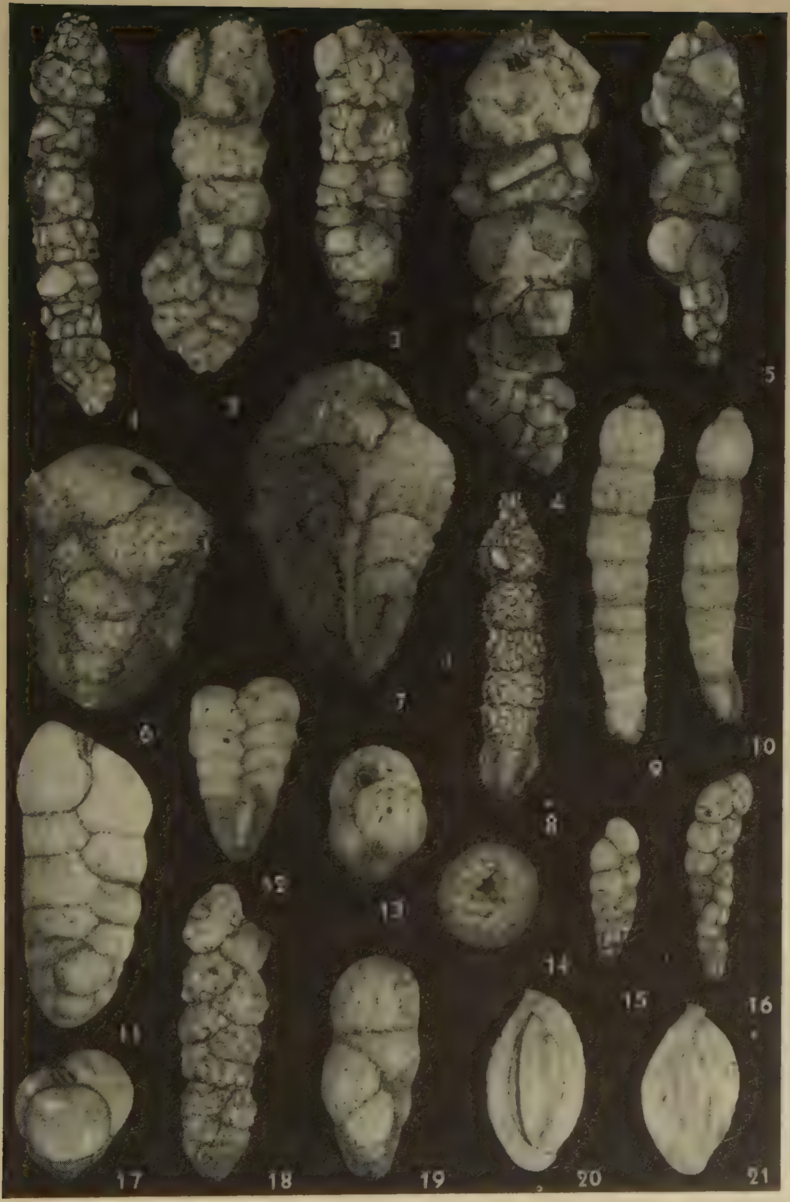
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Plate 3

PLATE 4

Figs. 1, 2. *Quinqueloculina bicostata* d'Orbigny. X 39. Sta. 93.

Figs. 3, 4. *Quinqueloculina horrida* Cushman. X 42. (3) Sta. 66; (4) Sta. 62.

Figs. 5, 6. *Quinqueloculina lamarckiana* d'Orbigny. X 39. Sta. 164.

Figs. 7, 8. *Quinqueloculina* cf. *polygona* d'Orbigny. X 42. Sta. 93.

Figs. 9, 10. *Quinqueloculina sabulosa* Cushman. X 42. (9) Sta. 214; (10) Sta. 93.

Figs. 11, 12. *Quinqueloculina* sp. X 42. Sta. 124.

Figs. 13, 14. *Quinqueloculina venusta* Karrer. X 42. Sta. 191.

Fig. 15. *Spiroloculina* cf. *grata* Terquem. X 42. Sta. 58.

Fig. 16. *Spiroloculina soldanii* Fornasini. X 42. Sta. 154.

Figs. 17, 21. *Sigmoilina distorta* Phleger and Parker. (17) X 70. Sta. 218; (21) X 62. Sta. 184.

Fig. 18. *Sigmoilina schlumbergeri* Silvestri. X 41. Sta. 107.

Fig. 19. *Sigmoilina tenuis* (Czjzek). X 62. Sta. 116.

Fig. 20. *Nummoloculina irregularis* (d'Orbigny). X 62.. Sta. 124.

Fig. 22. *Triloculina tricarinata* d'Orbigny. X 42. Sta. 121.

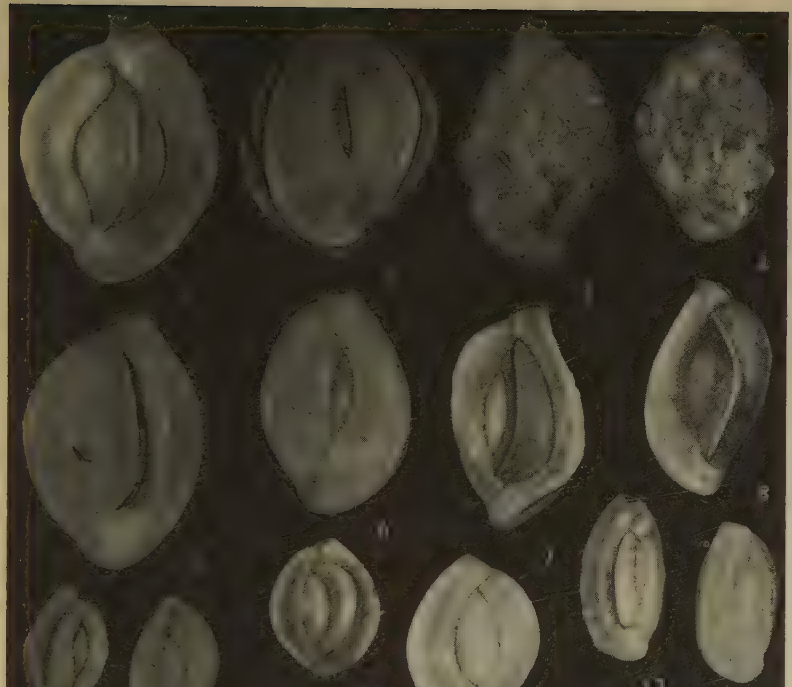
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Plate 4

PLATE 5

Fig. 1. *Sigmoilina* sp. X 33. Sta. 59.

Figs. 2, 3. *Triloculina* cf. *brevidentata* Cushman. X 42. Sta. 93.

Fig. 4. *Pyrgo* cf. *nasutus* Cushman. X 42. Sta. 93.

Figs. 5, 6. *Trochammina advena* Cushman. X 70. Sta. 24.

Fig. 7. *Pyrgo murrhina* (Schwager). X 39. Sta. 133.

Fig. 8. *Nodobaculariella cassis* (d'Orbigny). X 47. Sta. 93.

Figs. 9, 10. *Trochammina* cf. *japonica* Ishiwada. X 70. Sta. 24.

Figs. 11, 12. *Trochammina globulosa* Cushman. X 42. Sta. 36.

Fig. 13. *Wiesnerella auriculata* (Egger). X 70. Sta. 93.

Figs. 14, 15. *Trochammina quadriloba* Höglund. X 70. Sta. 191.

Figs. 16, 17. *Trochammina* cf. *tasmanica* Parr. X 70. Sta. 24.

Fig. 18. *Lenticulina peregrina* (Schwager). X 47. Sta. 199.

Fig. 19. *Nouria polymorphinoides* Heron-Allen and Earland. X 42. Sta. 225.

Fig. 20. *Nouria* sp. X 62. Sta. 27.

Fig. 21. *Marginulina marginulinoides* (Goës). X 33. Sta. 154.

Fig. 22. *Pseudoglandulina comatula* (Cushman). X 39. Sta. 116.

Fig. 23. *Globulina caribaea* d'Orbigny. X 62. Sta. 93.

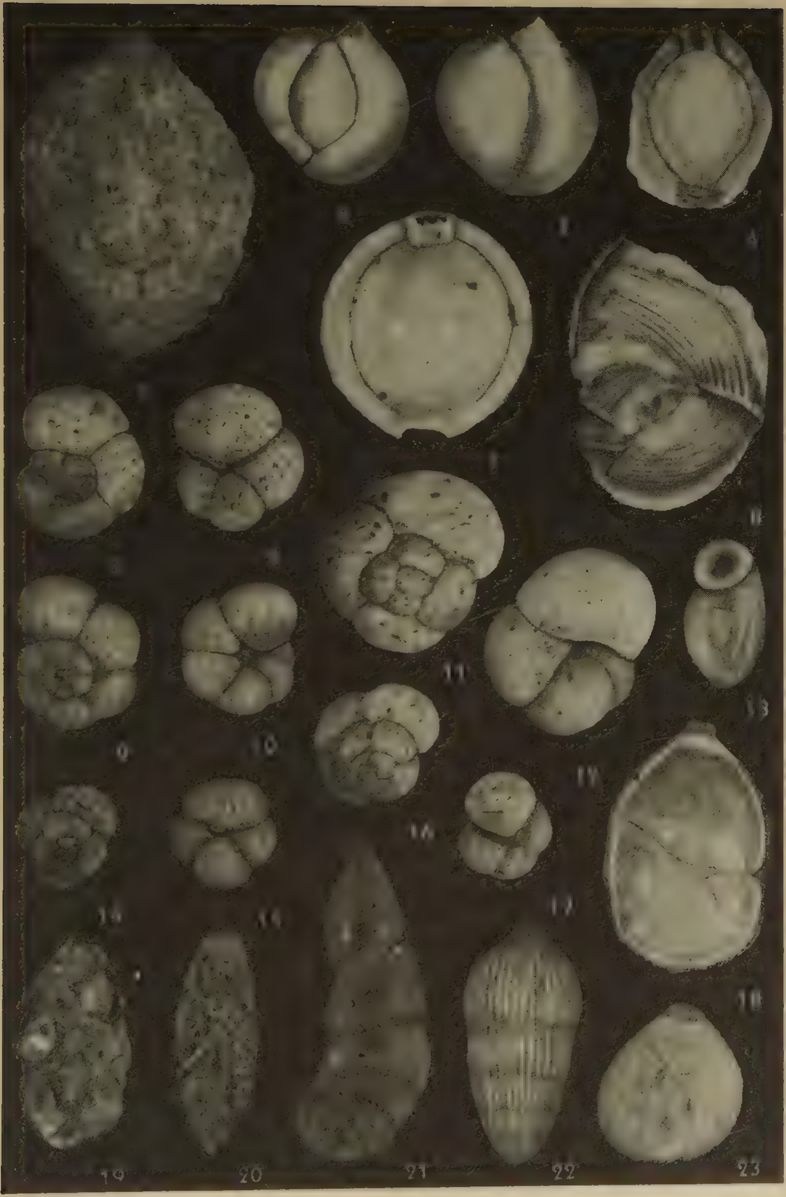
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Plate 5

PLATE 6

Fig. 1. *Nodosaria hispida* d'Orbigny. X 31. Sta. 187.
Fig. 2. *Guttulina australis* (d'Orbigny). X 42. Sta. 225.
Fig. 3. *Nonion formosum* (Seguenza). X 42. Sta. 154.
Fig. 4. *Nonion pompilioides* (Fichtel and Mol.). X 42. Sta. 2.
Fig. 5. *Astrononion tumidum* Cushman and Edwards. X 62. Sta. 189.
Figs. 6, 7. *Nonionella atlantica* Cushman. X 62. Sta. 222.
Figs. 8, 9. *Nonionella* sp. X 62. Sta. 224.
Figs. 10, 11, 12. *Nonionella opima* Cushman. X 62. Sta. 224.
Fig. 13. *Buliminella* cf. *bassendorfensis* Cushman and Parker. X 62. Sta. 28.
Fig. 14. *Elphidium advenum* (Cushman). X 42. Sta. 177.
Fig. 15. *Elphidium discoidale* (d'Orbigny). X 42. Sta. 222.
Fig. 16. *Elphidium gunteri* Cole. X 42. Sta. 93.
Fig. 17. *Elphidium poeyanum* (d'Orbigny). X 42. Sta. 93.
Fig. 18. *Robertina bradyi* Cushman and Parker. X 42. Sta. 124.
Fig. 19. *Bulimina aculeata* d'Orbigny. X 42. Sta. 105.
Fig. 20. *Bulimina marginata* d'Orbigny. X 62. Sta. 30.
Fig. 21. *Bulimina alazanensis* Cushman. X 62. Sta. 199.
Figs. 22, 23. *Bulimina spicata* Phleger and Parker. X 62. Sta. 32.
Fig. 24. *Bulimina striata mexicana* Cushman. X 42. Sta. 199.
Fig. 25. *Globobulimina affinis* (d'Orbigny). X 42. Sta. 34.

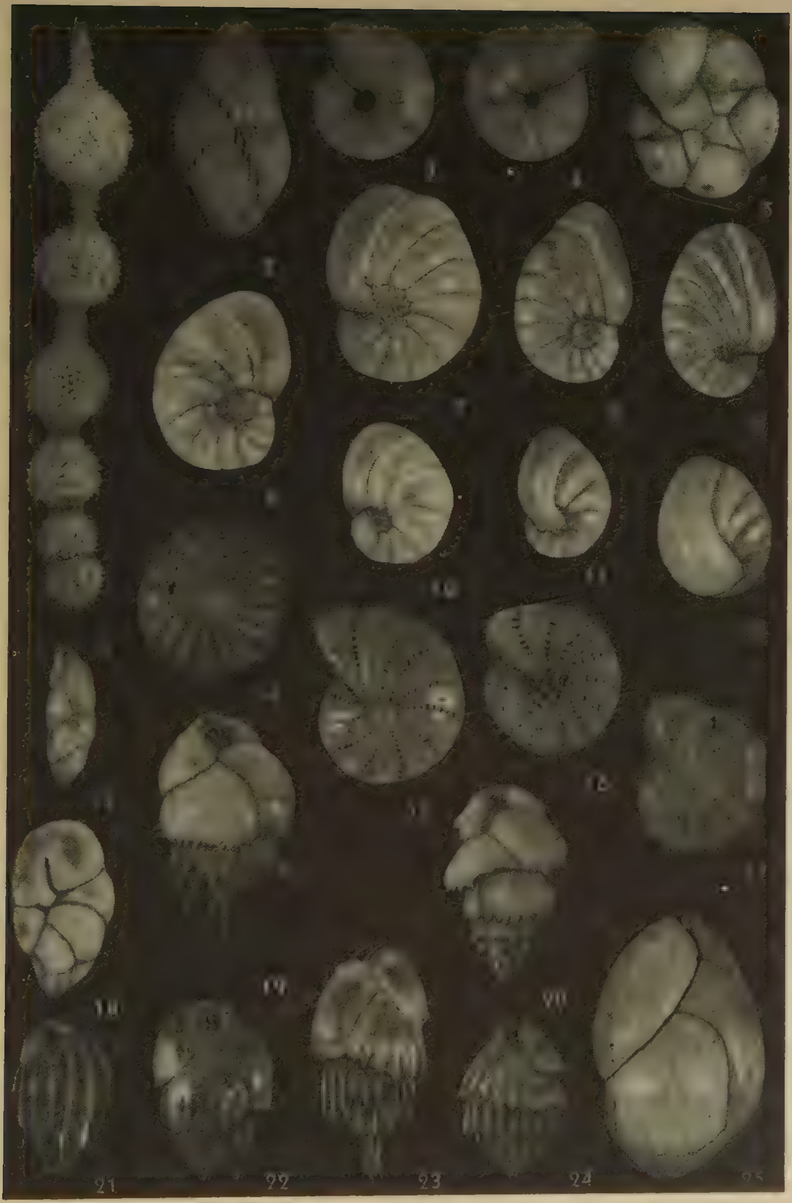

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PLATE 7

Fig. 1. *Globobulimina affinis* (d'Orbigny). X 46. Sta. 12.

Fig. 2. *Globobulimina affinis* (d'Orbigny) var. X 42. Sta.. 8.

Figs. 3, 4, 10. *Globobulimina mississippiensis* n. sp. X 62. Sta. 29. (3) Holotype; (4, 10) Paratypes.

Fig. 5. *Virgulina advena* Cushman. X 42. Sta. 191.

Fig. 6. *Virgulina complanata* Egger. X 62. Sta. 36.

Figs. 7, 8. *Virgulina mexicana* Cushman. X 42. Sta. 199

Fig. 9. *Virgulina pontoni* Cushman. X 62. Sta. 214.

Fig. 11. *Virgulina punctata* d'Orbigny. X 42. Sta. 93.

Fig. 12. *Virgulina tessellata* Phleger and Parker. X 62. Sta. 33.

Fig. 13. *Bolivina albatrossi* Cushman. X 62. Sta. 184.

Fig. 14. *Bolivina barbata* Phleger and Parker. X 62. Sta. 28.

Fig. 15. *Bolivina fragilis* Phleger and Parker. X 60. Sta. 76.

Fig. 16. *Bolivina goësii* Cushman. X 62. Sta. 116.

Figs. 17, 18, 19, 20. *Bolivina lanceolata* n. sp. X 62. Sta. 180. (17) Holotype; (18, 19, 20) Paratypes.

Fig. 21. *Bolivina lowmani* Phleger and Parker. X 70. Sta. 184.

Figs. 22, 23. *Bolivina minima* Phleger and Parker. X 62. Sta. 184.

Fig. 24. *Bolivina ordinaria* Phleger and Parker. X 70. Sta. 30.

Fig. 25. *Bolivina* sp. X 42. Sta. 190.

Fig. 26. *Bolivina paula* Cushman and Cahill. X 70. Sta. 122.

Fig. 27. *Rectobolivina advena* (Cushman). X 42. Sta. 57.

Fig. 28. *Reussella atlantica* Cushman. X 62. Sta. 58.

Fig. 29. *Bolivina striatula spinata* Cushman. X 62. Sta. 27.

Figs. 30, 35. *Bolivina subspinescens* Cushman. X 42. Sta. 116.

Fig. 31. *Bolivina pusilla* Schwager. X 62. Sta. 121.

Fig. 32. *Loxostomum abruptum* Phleger and Parker. X 70. Sta. 144.

Fig. 33. *Bolivina subaenariensis mexicana* Cushman. X 42. Sta. 184.

Fig. 34. *Bolivina translucens* Phleger and Parker. X 62. Sta. 184.

Fig. 36. *Bolivina pulchella primitiva* Cushman. X 70. Sta. 74.

Fig. 37. *Rectobolivina dimorpha* (Parker and Jones). X 62. Sta. 190.

Fig. 38. *Uvigerina auberiana* d'Orbigny. X 42. Sta. 128.

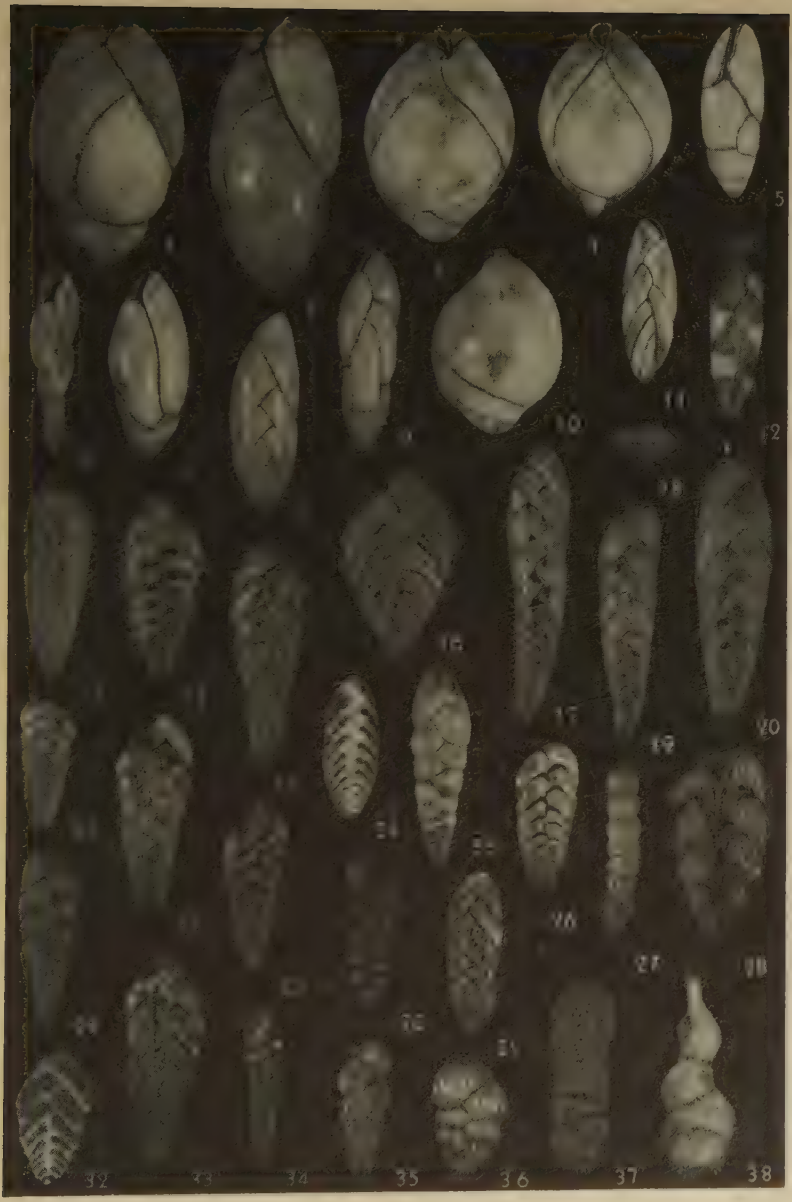
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Plate 7

PLATE 8

Fig. 1. *Uvigerina auberiana* d'Orbigny. X 39. Sta. 128.
Fig. 2. *Uvigerina flintii* Cushman. X 42. Sta. 116.
Fig. 3. *Uvigerina hispido-costata* Cushman and Todd. X 42. Sta. 187.
Fig. 4. *Uvigerina laevis* Goës. X 62. Sta. 76.
Fig. 5. *Uvigerina peregrina* Cushman. X 42. Sta. 128.
Fig. 6. *Uvigerina parvula* Cushman. X 62. Sta. 116.
Fig. 7. *Angulogerina bella* Phleger and Parker. X 62. Sta. 214.
Fig. 8. *Angulogerina jamaicensis* Cushman and Todd. X 70. Sta. 58.
Fig. 9. *Trifarina bradyi* Cushman. X 42. Sta. 141.
Figs. 10, 11, 12. ''*Discorbis*'' *bulbosa* n. sp. X 70. Sta. 220. (10) Holotype; (11, 12) Paratypes.
Figs. 13, 14. *Conorbina orbicularis* (Terquem). X 70. Sta. 161.
Figs. 15, 16. *Spirillina vivipara* Ehrenberg. X 70. Sta. 154.
Figs. 17, 18. *Rosalina* cf. *concinna* (H. B. Brady). X 62. Sta. 93.
Figs. 19, 20. *Rosalina floridana* (Cushman). X 62. Sta. 224.
Figs. 21, 26, 27. *Rosalina suezensis* (Said). (21) X 70; (26, 27) X 62. Sta. 52.
Figs. 22, 23. *Rosalina bertheloti* d'Orbigny. X 42. Sta. 179.
Figs. 24, 25. *Rosalina parkerae* (Natland). X 62. Sta. 154.
Figs. 28, 29. *Rosalina floridensis* (Cushman). X 30. Sta. 138.

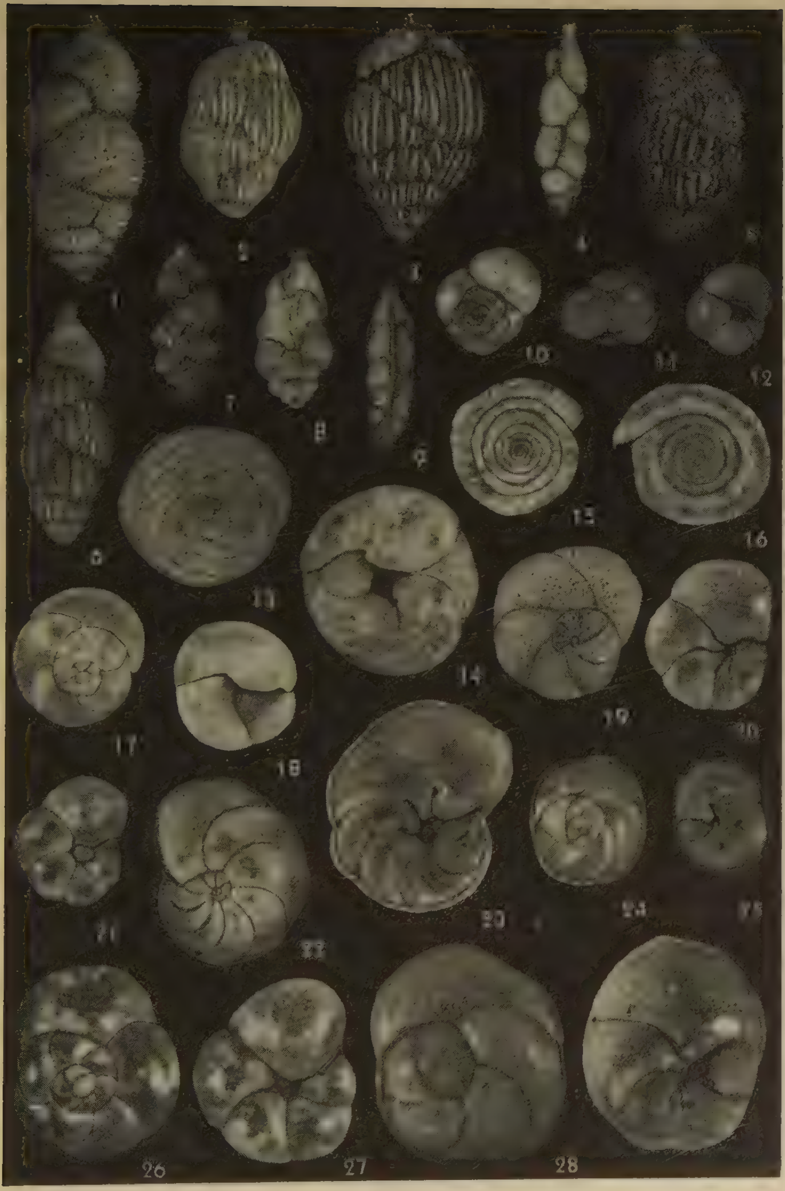
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Plate 8

PLATE 9

Figs. 1, 2, 3. *Valvulineria mexicana* n. sp. (1, 2) X 62; (3) X 70. (1, 3) Paratypes; (2) Holotype. Sta. 31.

Figs. 4, 5, 6. *Valvulineria minuta* n. sp. X 70. (4, 6) Paratypes; (5) Holotype. Sta. 184.

Figs. 7, 8. *Gyroidinoides soldanii altiformis* R. E. and K. C. Stewart. X 42. Sta. 190.

Figs. 9, 10 *Gyroidina neosoldanii* Brotzen. X 42. Sta. 191.

Figs. 11, 12. *Eponides polius* Phleger and Parker. X 62. Sta. 107.

Figs. 13, 18. *Gyroidina orbicularis* d'Orbigny. X 62. Sta. 184.

Figs. 14, 15. *Eponides antillarum* (d'Orbigny). (14) X 39; (15) X 42. Sta. 93.

Figs. 16, 17. *Eponides regularis* Phleger and Parker. X 70. Sta. 30.

Figs. 19, 24. *Eponides tumidulus* (H. B. Brady). X 94. Sta. 191.

Figs. 20, 21. *Pseudoeponides umbonatus* (Reuss). X 42. Sta. 107.

Figs. 22, 23. *Eponides turgidus* Phleger and Parker. X 70. Sta. 191.

Figs. 25, 26. *Buccella hannai* (Phleger and Parker). X 62. Sta. 93.

Figs. 27, 28. *Eponides repandus* (Fichtel and Moll). (27) X 39; (28) X 33. Sta. 179.

Figs. 29, 30. *Osangularia cultur* (Parker and Jones). X 42. Sta. 124.

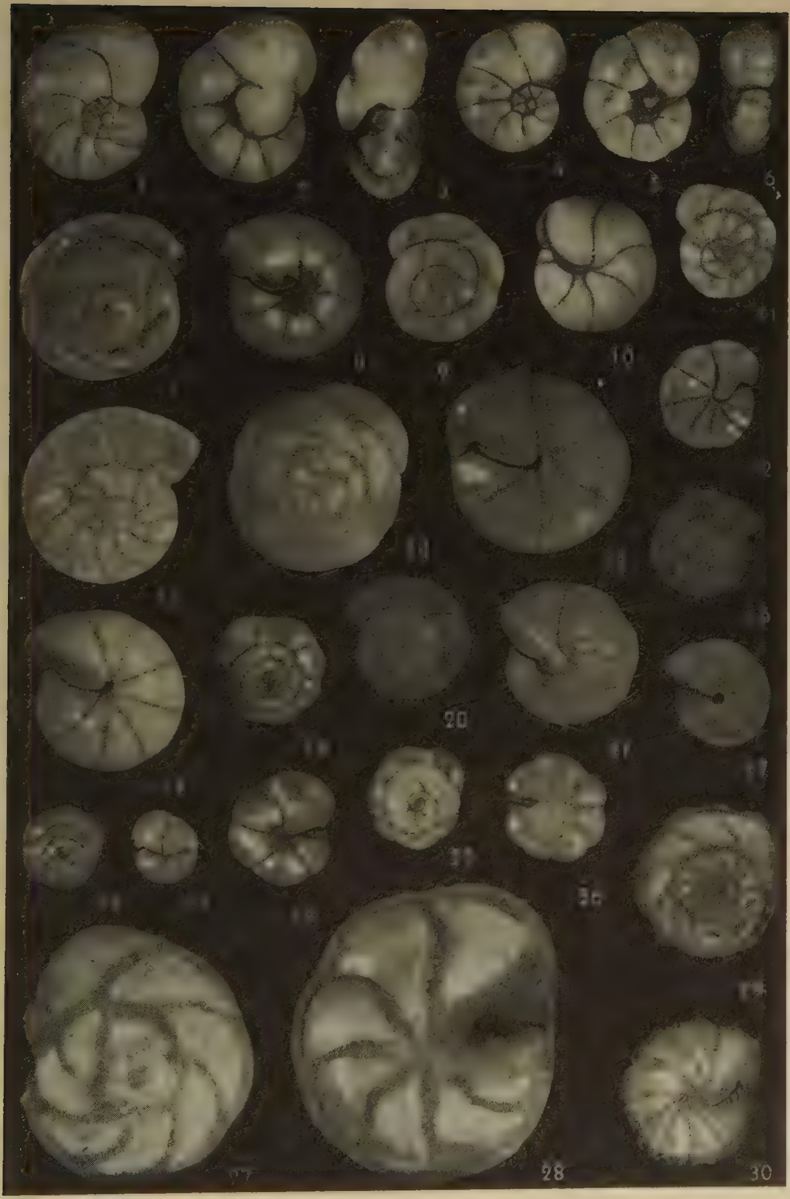

Plate 9

PLATE 10

Figs. 1, 2, 5, 6. *''Rotalia'' beccarii* (Linné) vars. X 62. Sta. 93.

Figs. 3, 7. *''Rotalia'' translucens* Phleger and Parker. X 70. Sta. 99.

Figs. 4, 8. *Höglundina elegans* (d'Orbigny). X 42. Sta. 116.

Figs. 9, 10. *Siphonina bradyana* Cushman. X 42. Sta. 141.

Figs. 11, 12. *Siphonina pulchra* Cushman. X 42. Sta. 179.

Figs. 13, 14. *Cancris oblonga* (Williamson). X 42. Sta. 52.

Figs. 15, 21. *Cancris sagra* (d'Orbigny). X 42. Sta. 93.

Figs. 16, 17. *Asterigerina carinata* d'Orbigny. X 42. Sta. 170.

Figs. 18, 19. *Epistominella decorata* (Phleger and Parker). X 70. Sta. 191.

Figs. 20, 26. *Epistominella vitrea* Parker. X 62. Sta. 27.

Figs. 22, 23. *Epistominella exigua* (H. B. Brady) X 62. Sta. 124.

Figs. 24, 25. *Epistominella rugosa* (Phleger and Parker). X 62. Sta. 141.

Figs. 27, 28, 29. *Stetsonia minuta* n. sp. X 94. (27) Holotype; (28, 29) Paratypes. Sta. 218.

Fig. 30. *Cassidulina carinata* Silvestri. X 42. Sta. 100.

Fig. 31. *Cassidulina* aff. *crassa* d'Orbigny. X 62. Sta. 116.

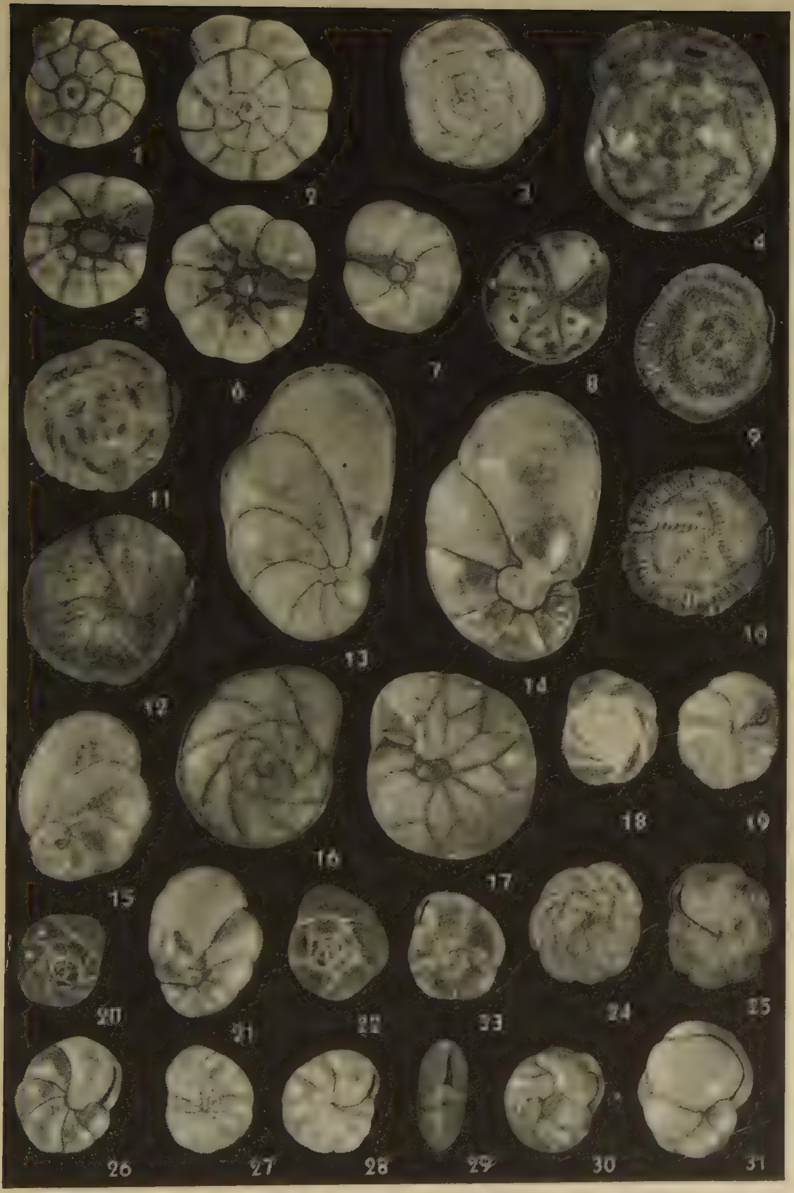
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Plate 10

PLATE 11

Fig. 1. *Cassidulina curvata* Phleger and Parker. X 42. Sta. 116.

Fig. 2. *Cassidulina laevigata* d'Orbigny. X 62. Sta. 78.

Fig. 3. *Cassidulina neocarinata* Thalmann. X 62. Sta. 184.

Figs. 4, 5. *Cassidulina subglobosa* H. B. Brady. X 62. Sta. 124.

Figs. 6, 7, 8, 9. *Cassidulina subglobosa* H. B. Brady vars. X 70. (6) Sta. 74; (7, 8, 9) Sta. 124.

Figs. 10, 11. *Rotamorphina laevigata* (Phleger and Parker). X 70. Sta. 184.

Fig. 12. *Ehrenbergina spinea* Cushman. X 62. Sta. 116.

Fig. 13. *Seabrookia earlandi* Wright. X 70. Sta. 179.

Fig. 14. *Cassidulinoides tenuis* Phleger and Parker. X 62. Sta. 188.

Fig. 15. *Chilostomella oolina* Schwager. X 62. Sta. 189.

Fig. 16. *Pullenia quinqueloba* Reuss. X 62. Sta. 179.

Fig. 17. *Pullenia bulloides* (d'Orbigny). X 42. Sta. 107.

Fig. 18. *Sphaeroidina bulloides* d'Orbigny. X 42. Sta. 116.

Fig. 19. *Sphaeroidina compacta* Cushman and Todd. X 39. Sta. 128.

Figs. 20, 24. *Pullenia* sp. X 70. Sta. 121.

Figs. 21, 22, 23. *Anomalinoides mexicana* n. sp. X 62. (21) Holotype; (22, 23) Paratypes. Sta. 184.

Figs. 25, 26. *Planulina foveolata* (H. B. Brady). X 42. Sta. 181.

Figs. 27, 30. *Planulina ariminensis* d'Orbigny. (27) X 30; (30) X 42. Sta. 141.

Figs. 28, 29. *Planulina exorna* Phleger and Parker. X 42. Sta. 93.

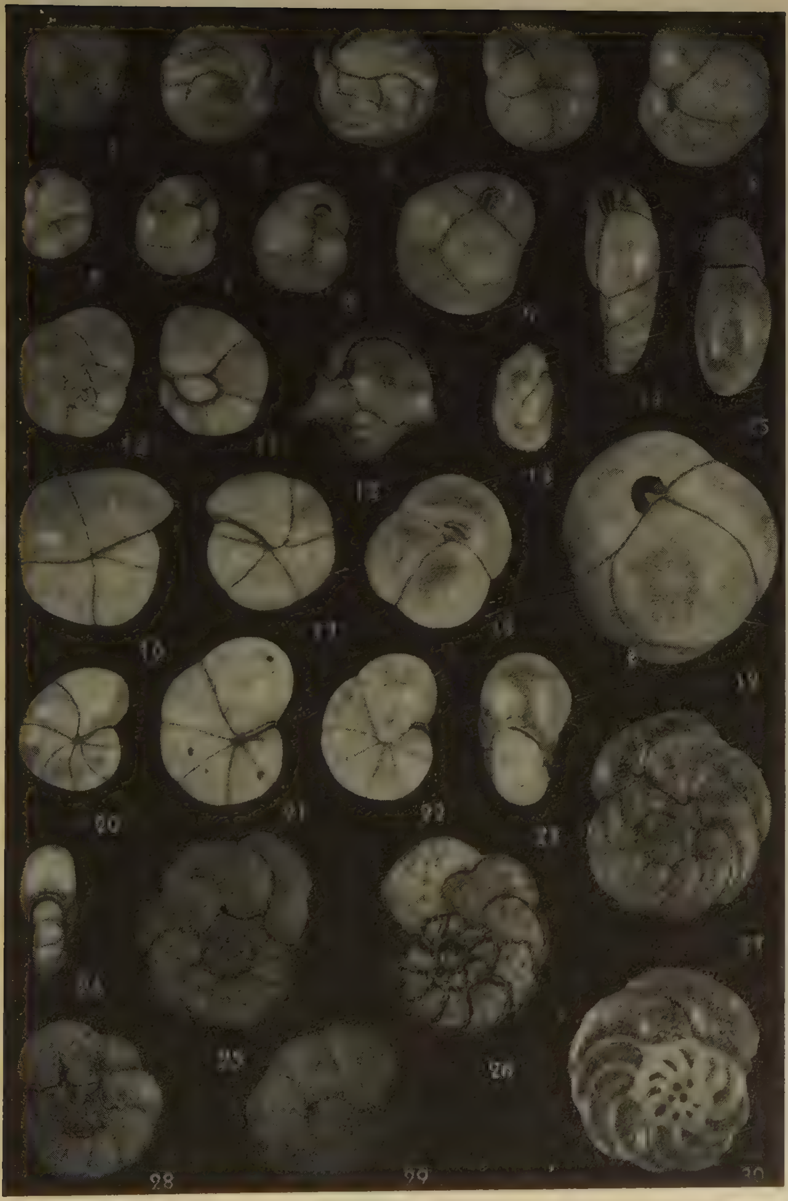
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Plate 11

PLATE 12

Figs. 1, 2. *Cibicides deprimus* Phleger and Parker. X 42. Sta. 154.

Fig. 3. *Laticarinina pauperata* (Parker and Jones). X 30. Sta. 191.

Figs. 4, 8. *Cibicides corpulentus* Phleger and Parker. X 39. Sta. 181.

Figs. 5, 9. *Cibicides* aff. *floridanus* (Cushman). X 42. Sta. 31.

Figs. 6, 7. *Cibicides io* Cushman. X 42. West of Sta. 78, at 62 m.

Figs. 10, 11. *Cibicides kullenbergi* Parker. X 42. Sta. 191.

Figs. 12, 15. *Cibicides mollis* Phleger and Parker. X 42. Sta. 76.

Figs. 13, 14, 16. *Cibicides protuberans* n. sp. (13, 14) X 39; (16) X 42. (13) Holotype; (14, 16) Paratypes. Sta. 116.

Figs. 17, 18. *Cibicides umbonatus* Phleger and Parker. (17) X 42; (18) X 39. Sta. 181.

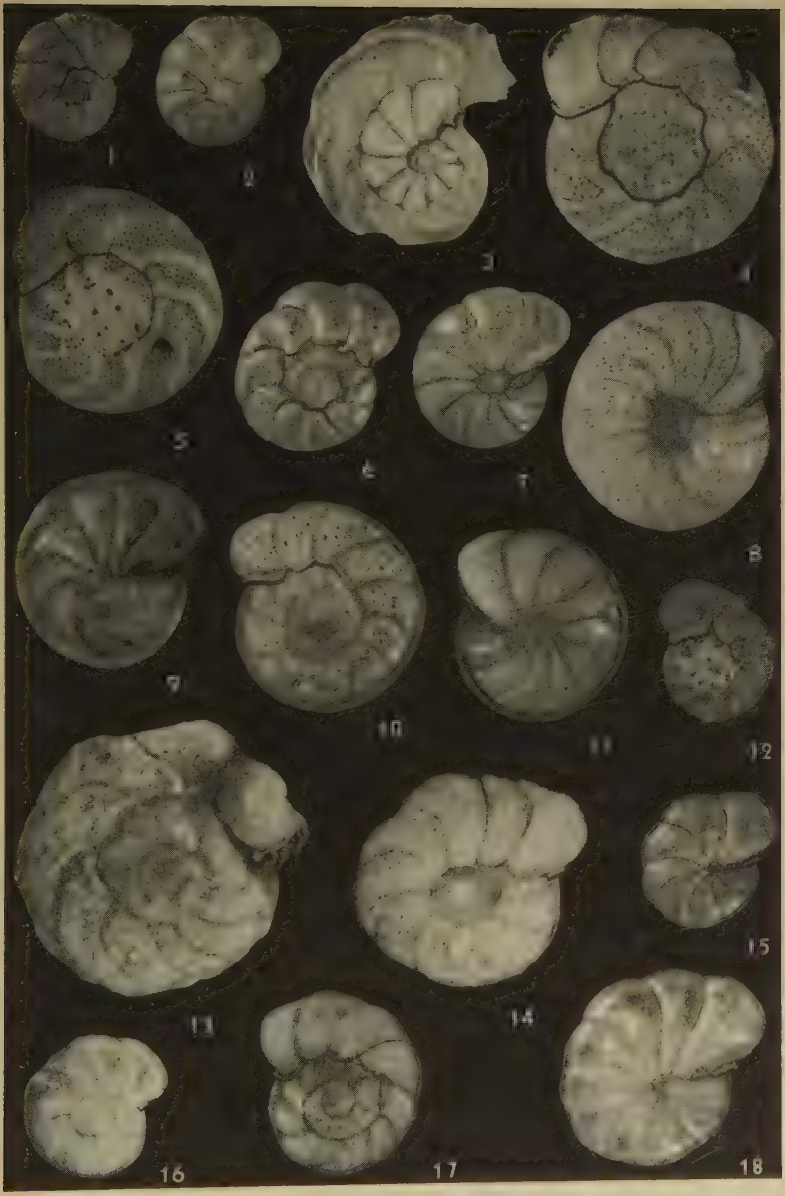
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Plate 12

PLATE 13

Figs. 1, 4. *Cibicides rugosa* Phleger and Parker. X 30. Sta. 124.

Figs. 2, 5. *Cibicides robertsonianus* (H. B. Brady). (2) X 42; (5) X 39. Sta. 191.

Figs. 3, 6. *Cibicides wuellerstorfi* (Schwager). X 42. Sta. 191.

Figs. 7, 10. *Cibicidina concentrica* (Cushman). X 42. Sta. 58.

Figs. 8, 11. *Cibicidina strattoni* (Applin). (8) X 42; (11) X 39. Sta. 93.

Fig. 9. *Planorbulina mediterranensis* d'Orbigny. X 30. Sta. 138.

Fig. 12. *Gypsina vesicularis* (Parker and Jones). X 34. Sta. 64.

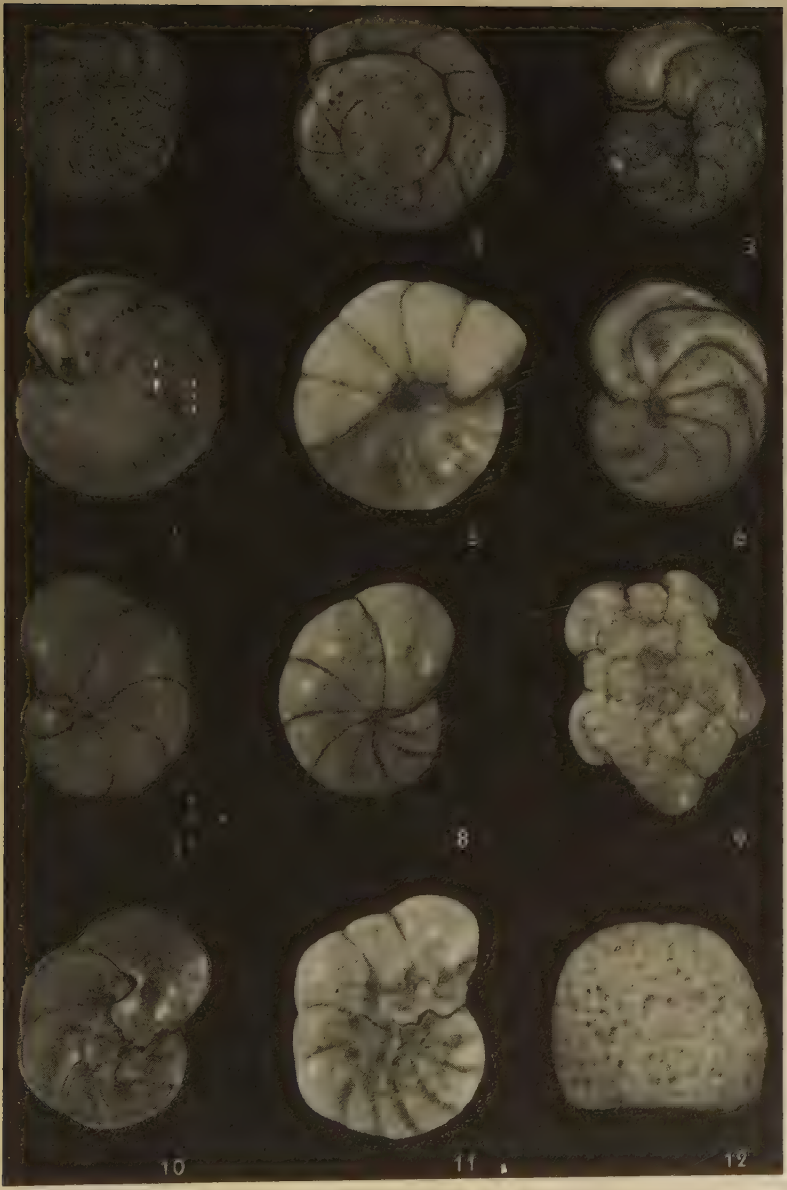

Plate 13

ERRATA

The following corrections should be made in Figures 3-9.

Figure 3. *Bolivina albatrossi* does not occur in traverse I.

Figure 4. *Canoris oblonga* does not occur in traverses II-III.
Cassidulinoides tenuis does not occur in traverses IV-V.
Cibicides kullenbergi occurs once in traverse V (not in IV).

Figure 5. "*Discorbis*" *bulbosa* occurs in traverse XI.
Elphidium gunteri occurs in traverse III (once).
Epistominella rugosa does not occur in traverse I. It occurs once in traverses II and III.

Figure 6. *Liebusella* spp. occurs in traverses II-III (once).
Marginulina marginulinoides occurs once in traverse V (not in IV).
Nodosaria hispida occurs deeper than 146 m.
Nonion pompilioides does not occur in traverses IV-V.
Nonionella opima occurs in traverse I.

Figure 7. *Quinqueloculina compta* occurs in traverse XI (once).
Q. sp. occurs in traverses II-III.
Rectobolivina advena occurs in traverse XI (once).

Figure 8. "*Rotalia*" *beccarii* vars. occurs in traverse I more than once.
Sigmoilina tenuis occurs in traverse III (once), V (more than once).
Siphonina pulchra occurs in traverse II (once).
Siphotextularia rolshauseni occurs in traverse II.
Sphaeroidina bulloides occurs in traverses II-III.

Figure 9. *Textularia earlandi* does not occur in traverses VI-VII.
Trochammina quadriloba occurs once in traverse VII (not in VI).
Valvulineria minuta occurs more than once in traverse II.
Virgulina pontoni occurs in traverse XI.
Wiesnerella auriculata occurs in traverse I (once), III (once).

STUDIES ON PLANKTON OF THE BERING AND CHUKCHI SEAS AND ADJACENT AREAS

By MARTIN W. JOHNSON, Scripps Institution of Oceanography

INTRODUCTION

INVESTIGATIONS on the zooplankton of the Bering Sea have been most fragmentary, and there appears to have been no studies whatever dealing with plankton in the open waters of the Chukchi Sea (also known as Chukotsk Sea) which is part of the Arctic Ocean lying north of the Bering Strait.

The Canadian Arctic Expedition of 1913-1918 issued a number of short taxonomic reports dealing with marine plankton collections taken along the Alaskan coast. See especially Willey (1920).

The present study on the biology of the plankton is based on two series of net collections each taken simultaneously with hydrographic observations made by the U.S. Coast Guard Cutter *Chelan* from July 26 to August 24, 1934, and the U.S.S. *Nereus* from July 27 to August 12, 1947.

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NUMBERS OF PRINCIPAL PLANKTON ORGANISMS TAKEN BY THE U.S.S. *NEREUS*

Station	N2	N3	N5	N6	N7	N8	N9	N10
Acartia longiremis	297	113	4,115	5,584	2,671	170	70	
Acartia nauplius				1,088	1,972	85	140	
Calanus cristatus	5							1
C. finmarchicus	30	341		26	175	55	257	25
C. tonsus	1	1					4	64
Centropages mcmurrichi								
Epilabidocera amphitrites				1				
Eucalanus bungii bungii	21	6					3	
Eucalanus nauplius	88	57					140	172
Metridia lucens		41						7
Microsetella								
Oithona similis	12,233	1,644	1,397	798	2,076	8,436	5,180	3,272
Oncaea borealis					1			
Pseudocalanus minutus	438	3,062	1	4,786	4,785	937	1,820	2,153
Tortanus discaudatus			2	3				
Calanoid nauplius						511	1,750	1,033
Euphausiid	1	2	2					1
Euphausiid larva			155					
Euphausiid egg			1			596	70	
Amphipod	10	1		1	13	8	19	39
Evadne								
Podon								
Appendicularia		284	1			3,420	1,260	258
Barnacle nauplius	172				4	8		173
Barnacle cypris	44							1
Crab larva	16	1	4	1	4		6	4
Annelid larva				1	6		2	
Lamellibranch larva	132	113	155	73	7,059	1,960	1,820	
Veliger larva	658	1,701					70	
Chaetognath 0-8mm.	19	11	78	334	364	47	1	8
Chaetognath 8-15mm.	160	6			4		2	
Chaetognath 15mm.	13			1	26		85	4
Bipinnarian	44		7					
Echinopluteus			1	162,739	1	170	2,030	
Ophiopluteus	219				623	257	420	

ND CHUKCHI SEAS, 1947. (ADJUSTED TO 60 METRES VERTICAL HAUL)

13	N14	N15	N16	N17E	N21	N22	N23	N28	N30	N46
52	1			1	6	296	3,530	1	68	2,605
							974		135	1,146
								1		
8	7	44	6	8	29	213		104	60	9
		1		1						
					3		111			7
					1					
					8	9				19
						1		1	1	
		1	1	2				1		
				1				1		
36	457	1,485	522	484	2,831	9,065	2,313	2,381	2,774	11,983
76	1,523	4,137	1,043	761	2,359	2,463	1,947	1,012	677	2,709
					1				1	
4	1,980	2,334	730	691		2,463	1,582	92	609	938
						2				11
		1			2					
2	1		1	1		3		6	3	6
					189		365			
					189		486			
8	2,129	849	107	78	1,038	986	1,826	92	1,962	729
	726	2,334	4	484	755		1	92		729
0	7	1,803	1	277	189	1	111		1	1
1	1	1		1		1	4	2		10
1	606	5,248	1	1	189	1	988		203	1,876
1	152	212	1		3,397	3,744	2,434	184	1,421	8,957
										3,960
2	5	49	6	9	44	93	19	13	19	
5	7	1		1		4	12	14	19	
1	1		10	1		15			3	
					189		1			521
					2,170	3,252	609		11,164	
					1,321	197	1		118	7,502

The *Chelan* occupied 102 plankton stations distributed along lines covering extensive stretches in both offshore and coastal waters of Bering Sea from the Aleutian Islands north through the Bering Strait to latitude 66° 46′ N., longitude 170° 01′ W. (Figure 1). The *Nereus* occupied seven plankton stations, on a line from the Hawaiian to the Aleutian Islands, one at Unimak Island and 20 from the Pribilof Islands northward into the Arctic to the edge of the polar ice pack at 72° N. Only the stations from the Aleutian Islands northward will be here considered in detail (Figure 3).

The collections are of special value because of the extensive area covered in so short a period of time on each cruise. They contribute materially to our slowly accumulating knowledge of these remote areas especially with respect to the study of animal production during the summer; and to an over-all picture of the distribution of both permanent and temporary plankton as related to hydrographic features. A report pertaining to the *Chelan* collections was prepared for the Coast Guard (Johnson, 1934a).

The present report presents new data from the *Nereus* cruise, and it is desirable at the same time to integrate the results of the two cruises taken in much the same areas, but thirteen years apart, and to make the results generally available to interested civilian investigators. Tables for the 1934 plankton counts, including the more infrequent forms not here discussed can be found in the Coast Guard report. Table 1 includes counts of the principal forms taken in 1947. Station N32 is omitted from the table since the sample was not complete but it is included in the figures for locality records. The physical and chemical data for the 1934 *Chelan* cruise are discussed in detail by Barnes and Thompson (1938), and the *Nereus* cruise by LaFond, Dietz, and Pritchard (in press). The phytoplankton collected simultaneously with the zooplankton by Dr. L. D. Phifer during the *Chelan* cruise was studied by Phifer (1934). The net samples for 1947 were collected by E. C. LaFond, and R. S. Dietz. Dorothy Rubright assisted in analysis of the 1947 material.

Procedure: The *Chelan* used a 25 cm. net constructed of No. 20 bolting silk. The hauls were made vertically from a depth of 25 metres to the surface while the ship was hove to. The *Nereus* employed a 40 cm. net 1·5 metres long, constructed of No. 8 bolting silk, and at all stations except those in the Hawaiian section it was operated vertically from the bottom, usually 40 to 60 metres, to the surface.

The counts of organisms obtained for each haul give only relative concentrations of the more numerous and slowly moving forms especially copepods and larvae, but the pattern of distribution and its correlation with hydrographic features are such that the distribution and numbers are believed to give a fairly accurate portrayal of the major prevailing summer communities.

Plankton volumes were determined only for the 1947 cruise. In Figure 3 is given the relative volume (measured by displacement) of total plankton adjusted to 60 metre hauls for comparison. Both zoo- and phytoplankton are included, hence the figures represent total particulate organic material screened from the water by means of this type net. Usually the bulk, which in no case was large, was made up of zooplankton, but at stations N11, N14, and N16 the bulk was due

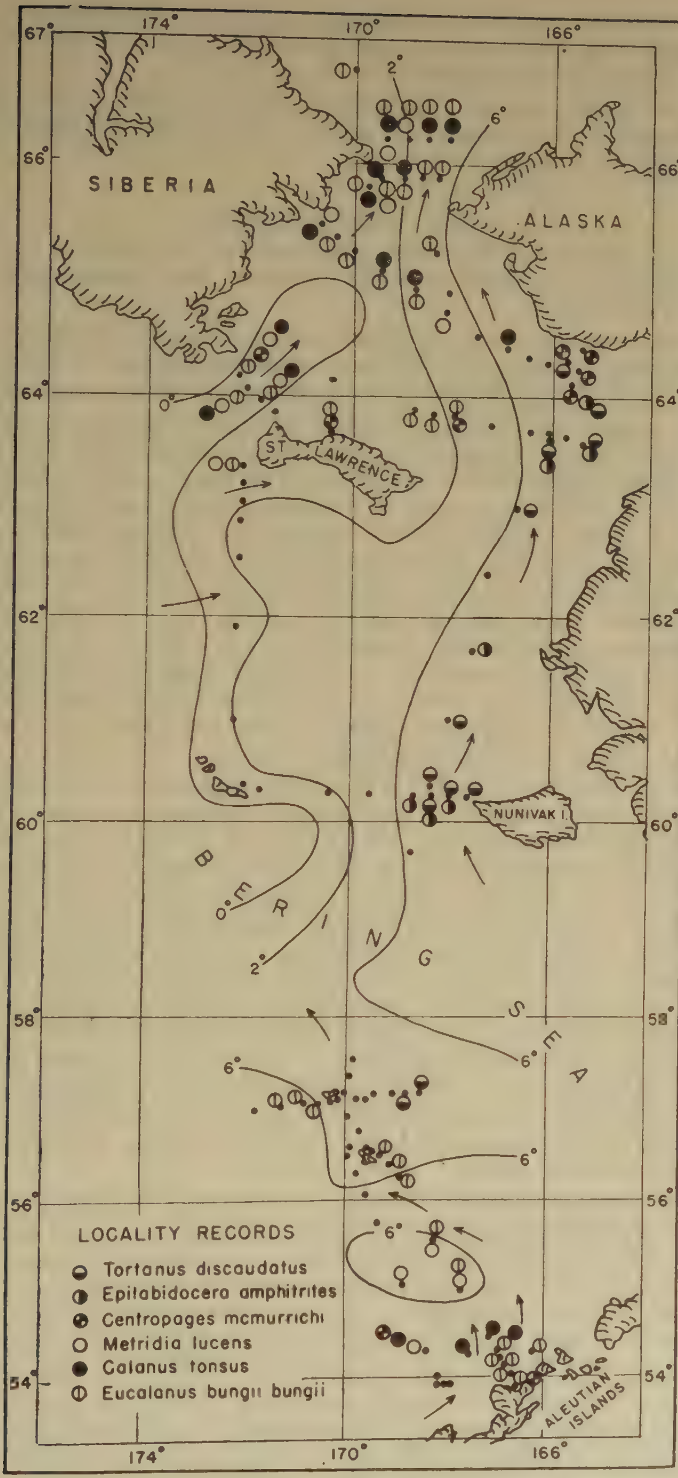

SIBERIA
ALASKA
ST LAWRENCE
NUNIVAK I.
BERING SEA
ALEUTIAN ISLANDS
67°
66°
64°
62°
60°
58°
56°
54°
174°
170°
166°
0°
2°
6°
LOCALITY RECORDS
Tortanus discaudatus
Epilabidocera amphitrites
Centropages mcmurrichi
Metridia lucens
Calanus tonsus
Eucalanus bungii bungii

FIG. 1.—Distribution of certain copepods in 1934. The *Chelan* plankton stations are shown as small dots. The isotherms (Centigrade) are for the 25 metre depth.

mainly to diatoms especially *Thalassiosira rotula, Thalassiosira nordenskioeldii, Fragilaria striatula,* and *Nitzschia seriata.* At N16 *Fragilaria* was overwhelmingly dominant.

In all cases the volumes are certainly minimal, since much of the finest material passes through the meshes of the net, and larger fast-swimming forms escape it.

THE ZOOPLANKTON POPULATION

Copepods constituted the major constituent of the plankton on both cruises though echinoderm and clam larvae, and appendicularians were often dominant.

From the following list of copepods certain of the species have been included in Figures 1 and 4 because of their characteristic distribution in relation to hydrographic features of inshore or offshore waters:

Acartia clausii Giesbrecht was taken in the *Chelan* cruise only in the vicinity of Nome, Alaska at stations C32, C33, and C57, and none were observed in the *Nereus* collections. This species thrives best in a neritic habitat with warm water of reduced salinity, and although not typically an Arctic species, it was reported by Willey (1920) in his analysis of the Canadian Arctic Expedition's plankton, from as far north as Point Barrow, Alaska. This northward extension of distribution to latitudes, unusually high for the species, is correlated with the northward flow of Bering Sea water through the Straits as evidenced by the hydrographic observations. Other fragments of biological information which will be mentioned below lend support to this contention. *A. clausii* is a common copepod along the Pacific coast and is abundant at times at La Jolla, California.

Acartia longiremis (Lilljeborg) is widely distributed in the surface water of the Bering and the Chukchi Seas. Adults were taken at 55 per cent of the *Chelan* stations and 85 per cent of the *Nereus* stations. If the species were represented at all stations where *Acartia* juveniles and nauplii were taken, the number of *Chelan* stations of occurrence is increased to 75 per cent. It is probable that the larvae and juveniles were mainly of this species. *A. longiremis* is more oceanic than *A. clausii,* and its regular distribution extends far into the Arctic and for that reason its presence north of the Bering Strait would not necessarily indicate that its presence is a northward extension of the Bering Sea population by way of the Strait. Its distribution in these surveys places it mainly with the neritic community on the Alaskan coast. There were decidedly fewer on the Siberian side. In 1947 active reproduction was taking place especially in areas of Norton and Kotzebue Sounds and Unimak Island.

Calanus cristatus (Kröyer). This unusually large copepod occurred at eight *Chelan* stations, particularly in the Bering Strait, and between Siberia and St. Lawrence Island. In 1947 it occurred at three stations, one near the Pribilofs, and two in the western portion of Bering Strait. It is known to be one of the important constituents of the North Pacific offshore and deep-water plankton. Samples examined from deep water of the Gulf of Alaska, and south of the Aleutian Islands indicate that it is one of the most numerous among the larger copepods there. It was present in *Nereus* samples from Lat. 43° 29′ N., Long. 171° 00′ W., and in 1939 two specimens were found in deep hauls by the *E. W. Scripps* 300 miles offshore in the latitude of Pt. Fermin, California.

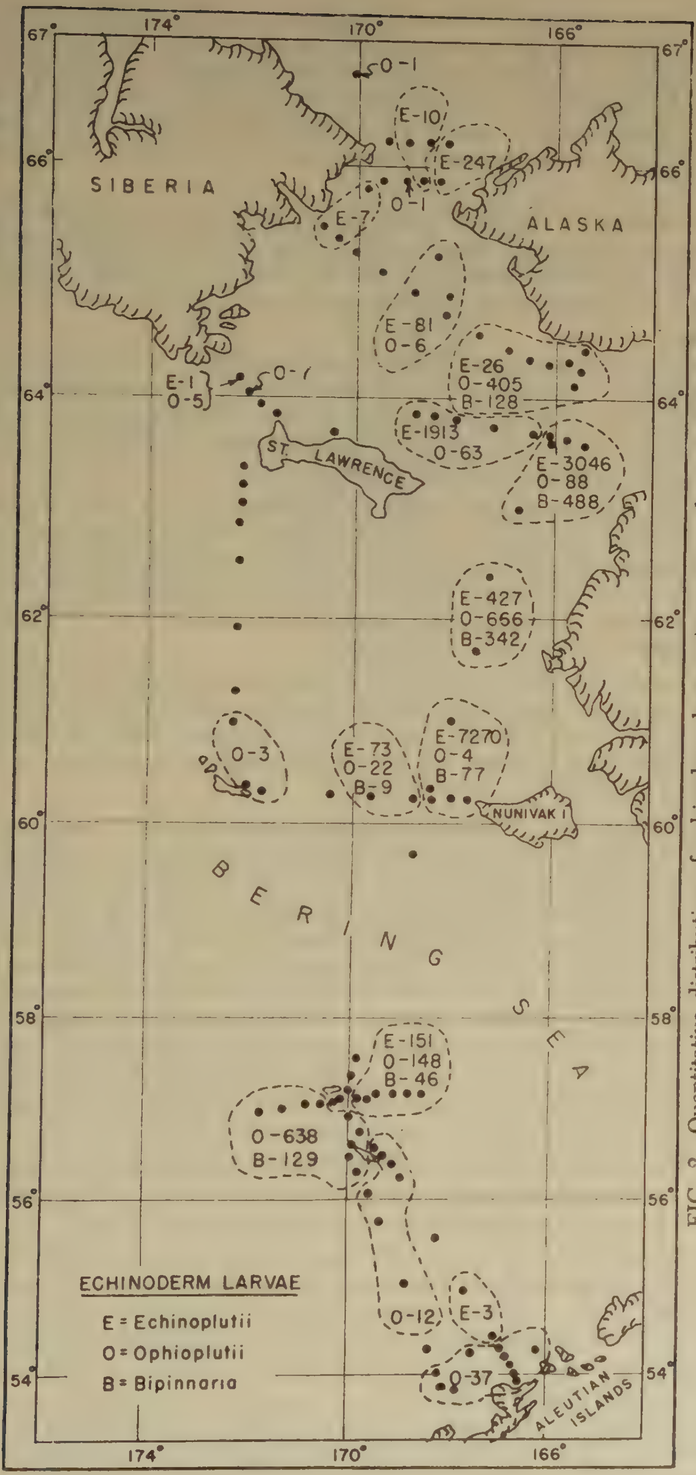

174°
170°
166°
67°
66°
64°
62°
60°
58°
56°
54°
SIBERIA
ALASKA
O-1
E-10
E-247
E-7
O-1
E-81
O-6
E-26
O-405
B-128
E-1
O-5
O-1
ST. LAWRENCE
E-1913
O-63
E-3046
O-88
B-488
E-427
O-666
B-342
O-3
E-73
O-22
B-9
E-7270
O-4
B-77
NUNIVAK I
BERING SEA
E-151
O-148
B-46
O-638
B-129
O-12
E-3
O-37
ALEUTIAN ISLANDS
ECHINODERM LARVAE
E = Echinoplutii
O = Ophioplutii
B = Bipinnaria

FIG. 2.—Quantitative distribution of echinoderm larvae. Average number of specimens taken in 25 metre hauls at stations enclosed in broken lines. U.S. C. G. C. *Chelan* 1934.

Calanus finmarchicus (Gunner) was taken at fifty *Chelan* stations distributed along all the sections with the exception of that south of St. Paul Island. It is probable that its distribution in that area is to be looked for below the level at which the net fished, for it is known to seek relatively deeper water in the intermediate layers when this is possible. It was present in small numbers at all but one of the *Nereus* stations.

The occurrence of *Calanus tonsus* Brady is shown in Figures 1 and 4. Its greatest frequency was in the colder waters flowing from the west and in the Straits northward into the Arctic. It is perhaps second to *Calanus finmarchicus* in importance among the large copepods of the region.

Centropages mcmurrichi (Willey) was present at widely separated stations (Figures 1 and 4). This species evidently prefers the inshore conditions, but may be expected also in more oceanic waters. Willey (1920) found it, and also the following species in collections from north of the Bering Strait on the Alaskan side.

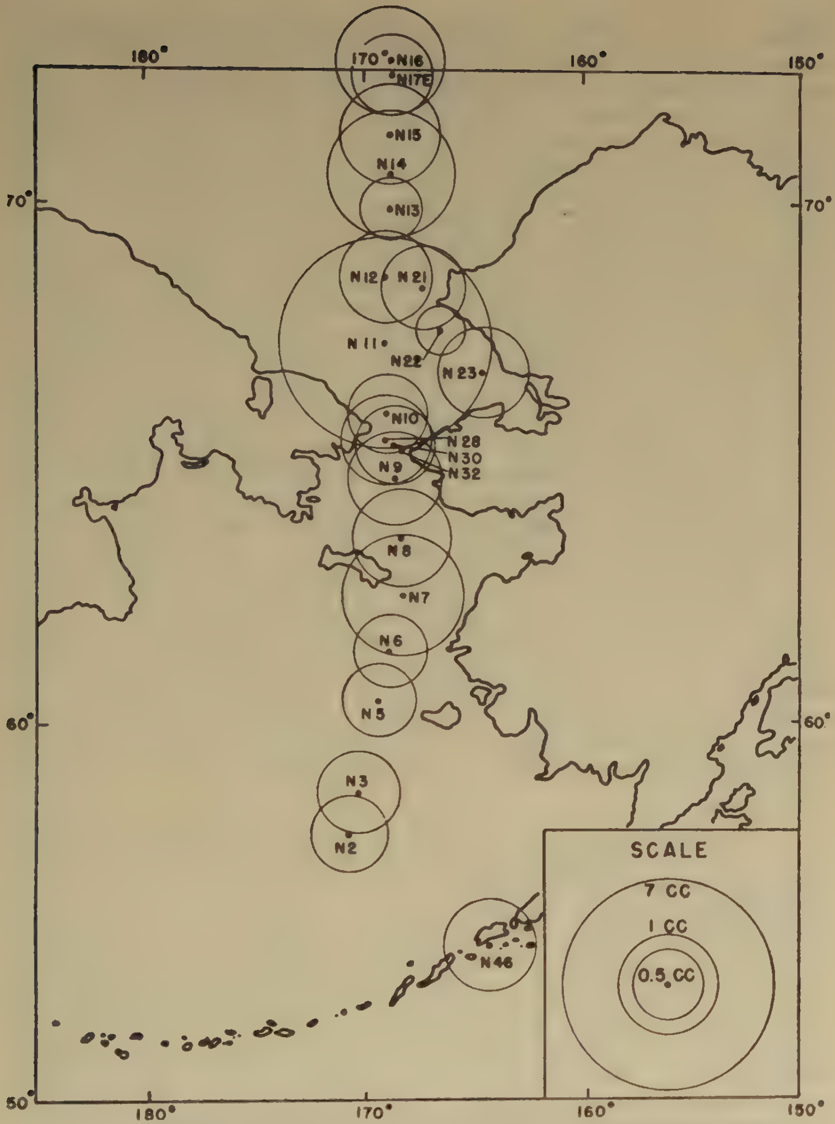
Epilabidocera amphitrites (McMurrich) was taken only in small numbers mainly in the larval stages. The seven *Chelan*, and two *Nereus* stations where it was taken are in Alaskan neritic waters (Figures 1 and 4). Willey (1920) records it from latitude 68° 30′ N. within the Arctic circle on the Alaskan coast. Southward it ranges to San Francisco Bay (Esterly, 1924).

In the study of *Chelan* samples, it was brought out that only the northern variety of *Eucalanus bungii* (see Johnson, 1938) occurred in the Bering Sea area. The *Nereus* series of samples verify this finding. The extensive area covered by the *Nereus* makes possible a further comparison of that interesting species.

In the series of stations occupied between the Aleutian and Hawaiian Islands, it was found that only the northern variety, *Eucalanus bungii bungii* was present at 43° 29′ N. latitude, and at stations north of that point, whereas at the next station south (38° 49′ N. latitude) it was almost completely replaced by the southern variety, *Eucalanus bungii californicus*. In the sample taken at this station only two adult specimens of the northern variety were found among forty specimens of the southern variant. The *Nereus* bathythermograph records show about 5° C. difference in surface temperature between these stations. On the west coast of North America the two varieties overlap along the Oregon coast and southward to Cape Mendocino, California.

E. bungii bungii is a major constituent in the Gulf of Alaska plankton, and is one of the most common species in the deep northern waters of Japan (Tanaka, personal communication, 1948).

The horizontal distribution of *E. bungii* in the Bering Sea indicated that it belonged typically to the western deeper portion of the sea, and as such was found mainly in regions characterized by north-eastward moving water of higher salinities, and lower temperatures (Figures 1 and 4). For example, it was found between Unalaska Island and the Pribilof Islands, and also west of the latter, and to the north along the Siberian coast, and in that portion of Bering Strait which is most characterized by water from the south-west. One might expect to find the species along the section from St. Lawrence Island to St.


180°
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N16
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N13
N12
N21
N11
N22
N23
N10
N28
N30
N32
N9
N8
N7
N6
N5
N3
N2
N46
SCALE
7 CC
1 CC
0.5 CC

FIG. 3.—Plankton displacement volumes adjusted to 60 metre hauls. The 1947 U.S.S. *Nereus* station numbers are also indicated.

Matthews, but here the surface waters were sparsely populated by any species. The 1947 samples show a somewhat more northern and eastern distribution than occurred in 1934. All stages of larval development were found on both cruises indicating successful reproduction in July and August. The distribution of the species and the proportions of developmental stages in the Bering Sea for 1934 have been reported elsewhere (Johnson, 1938). In 1947 nauplius larvae were taken at various stations up to N12 off Cape Lisburne.

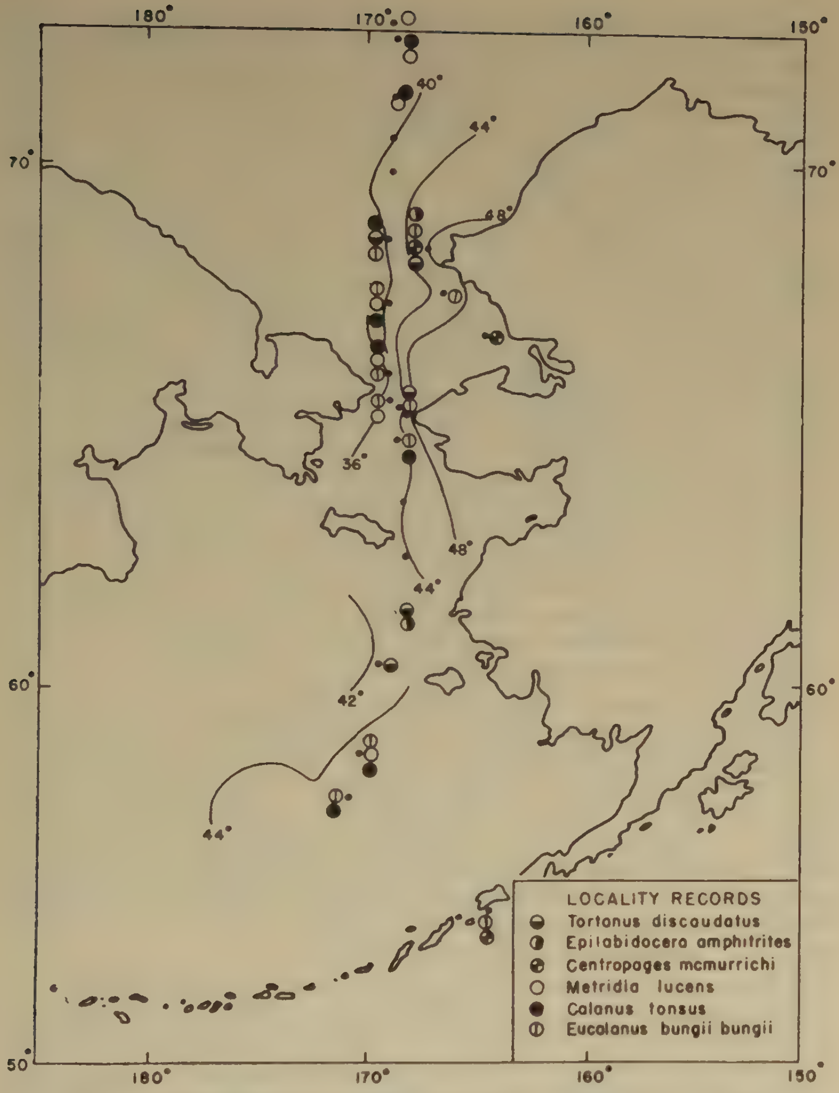
Eurytemora herdmani (Thompson and Scott) was noted only near the Pribilof Islands and off the entrance to Norton Sound. It was not found in 1947. The Canadian Arctic Expedition had it at stations in the Bering Sea and along the Arctic coast of Alaska and Canada.

Metridia lucens Boeck was taken at some of the more oceanic stations, placing it in the community characterized by *Eucalanus bungii, Calanus tonsus,* and *C. cristatus* (Figures 1 and 4). It is a wide ranging species occurring in offshore waters from Southern California to the northernmost *Nereus* station at the edge of the Arctic ice. A number of the specimens included in the table were juveniles, and had not yet developed specific characters, but in each instance where identification was possible, only *M. lucens* was present both in 1934 and 1947. The absence of the "Arctic" species, *M. longa* (Lubbock), in the Bering Sea in summer might indicate an absence of southward transportation of Arctic species through the Bering Strait, in summer. However, it was also absent from the *Nereus* stations far north of the Strait. It has, however, been reported by Campbell (1929) from the Vancouver Island region, by Marukawa (1928) from the Japan Sea and by Wilson (1942) chiefly in the north-western part of the north Pacific. Willey (1920) found it at stations situated only north of the Bering Strait.

Microsetella sp. was represented only as juveniles between the Aleutian and Pribilof Islands and in the Bering Strait in 1934, and in the Strait and in the Arctic in 1947.

Oithona similis was found by Willey (1920) to be generally distributed over the area covered by the Canadian Arctic Expedition. In the present investigation Table 1 shows clearly the abundance and extensive distribution of this little copepod over the whole area covered by the *Nereus*. At only one *Chelan* station was it absent from the collection. A large number of larvae, which are easily identified by reference to the work of Oberg (1906), were everywhere abundant or well represented except at three stations on the Siberian side of the Strait, showing that an extensive reproduction was taking place in all sections during the 1934 cruise. (The coarse meshed net used in 1947 apparently permitted these tiny larvae to escape, since very few were found.) This species must be considered a very important constituent of the surface plankton for the whole area during summer. It is probable that *Oithona* frequently plays a greater role in the plankton community than may be indicated in many plankton investigations where the coarse meshed nets employed are designed to catch only the larger animals. Its widespread distribution in the Bering and Chukchi Seas is in keeping with its well-known eurythermic and euryhaline character.

Oncaea borealis. These small copepods appear in general to belong mainly to that part of the area with the higher salinities and lower temperatures. Willey (1920) found *O. conifera* only along the Arctic coast.



180°
170°
160°
150°
70°
70°
60°
60°
50°
180°
170°
160°
150°
40°
44°
48°
36°
48°
44°
42°
44°
LOCALITY RECORDS
Tortonus discaudatus
Epilabidocera amphitrites
Centropages mcmurrichi
Metridia lucens
Calanus tonsus
Eucalanus bungii bungii

FIG. 4.—Distribution of certain copepods in 1947. The *Nereus* plankton stations are shown as small dots. The isotherms (Fahrenheit) are for the surface.

Pseudocalanus minutus (Kröyer). What was said above for *O. similis* applies rather well for this species also. The numbers were, however, somewhat less, and relatively fewer adults were taken. The greater vertical range of maximum distribution characteristic of this species as compared with *O. similis* would explain its fewer numbers in shallow plankton hauls, though the shoal water over much of the area would tend to keep it within the range sampled by the net.

Tortanus discaudatus (Thompson and Scott) was present only in waters of neritic and estuarine character along the Alaskan coast except at N12 off Cape Lisburne (Figures 1 and 4). On the west American coast it has a wide distribution, having been found as far south as La Jolla, California (Johnson, 1942). It is, however, not confined to the American Continent as formerly indicated for it has now been found also in the coastal waters of Northern Japan (Mori, 1937). But in the absence of thorough surveys in neritic waters along the coast of Siberia it is not possible to judge whether the connection is by way of the Bering Strait or to the south along the Aleutian Peninsula. Its eggs appear especially adapted for flotation (Johnson, 1935a) but their resistance to adverse conditions have not been studied. At temperatures of 10-12° C. they hatch in about four to five days. In tests the empty cases resisted decay over a period of at least 95 days. Thus if the eggs can remain dormant this long they would be accorded good surface protection during that time and might be transported considerable distance across areas adverse to the adults.

Among the pelagic larvae of bottom living animals, none were so conspicuous as certain echinoderm larvae. In 1934, practically the whole eastern area of the Bering Sea gave abundant evidence of heavy echinoderm spawning. Very few larvae were taken anywhere on the Siberian side. No larvae of Holothuroidea were found, though some early auricularia may have entered into the counts of bipinnarian larvae. The absence of holothuroidean "doliolaria" larvae may be accounted for by a short spawning period coupled with a relatively short pelagic life during which time the larvae float at the immediate surface as has been observed in Puget Sound.

Echinopluteus larvae of echinoids were well distributed over the eastern section (Figures 2, 5). The maximum number for one haul was about 162,000 in 1947, and 15,000 in 1934. It is significant that in 1934 the largest numbers were taken off Nunivak Island at stations C24 and C91, which are closely adjacent, but were occupied eleven days apart. Large numbers also occurred along the line from Nunivak Island to Nome, especially at the entrance to Norton Sound. On the Siberian side, only relatively few larvae were taken, but sufficient to indicate that a fair amount of spawning had occurred near the coast.

In 1947 echinoplutei were taken from station N5 northward to N12 (Figure 5). The greatest numbers occurred in the same general area as in 1934, i.e., off Cape Romanzof, and were perhaps the product of recent spawning in or near the area where caught, since the larvae were mostly in the 4 arm stage. Other successful *Nereus* hauls were in water with considerable thermal stratification, but in the band of relatively warm surface water extending out from the Alaskan Coast. Immediately north of the Bering Strait (stations N10, N27, and N11) where the surface isotherms are bent towards the east by cold water flowing along the western portion of the strait, no echinoplutei were

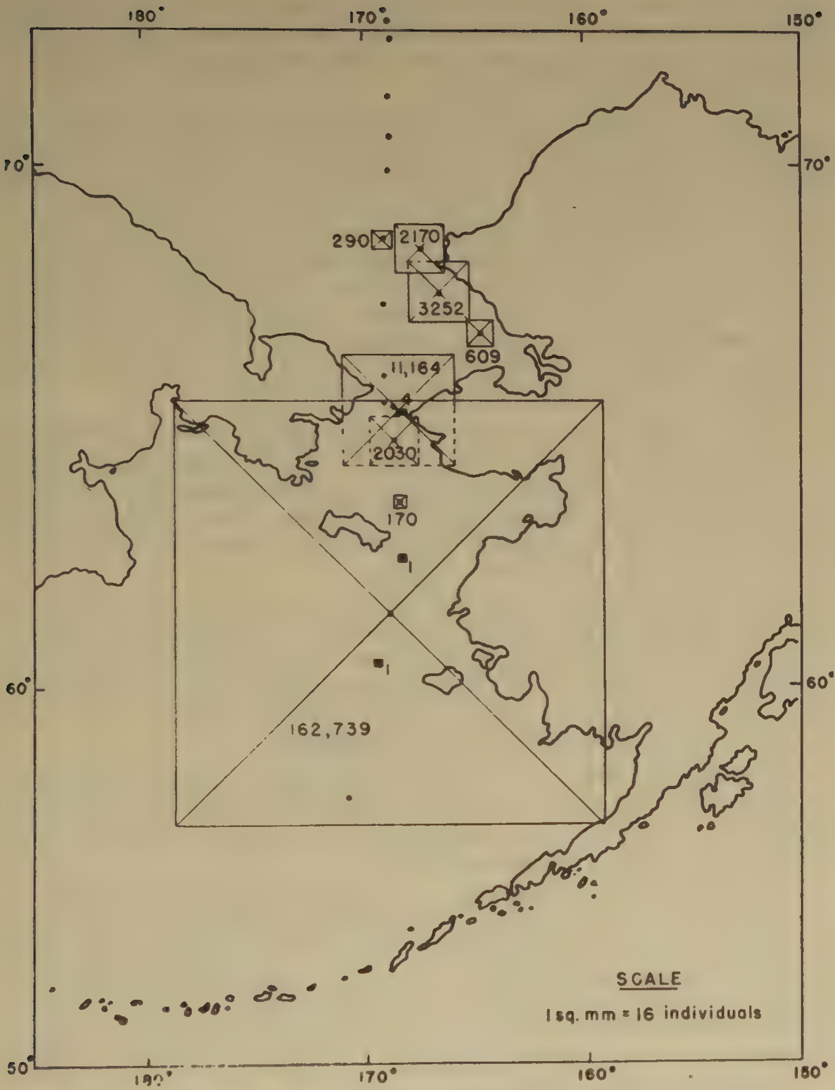

180°
170°
160°
150°
70°
60°
50°
290
2170
3252
609
11,164
2030
170
1
1
162,739
SCALE
1 sq. mm = 16 individuals

FIG. 5.—Echinopluteus. Numbers per haul, adjusted to 60 metre vertical hauls. U.S.S. *Nereus*, 1947.

taken, but at stations N12, N21, and N22, where the warm water from the Cape Lisburne and Kotzebue Sound areas is again felt at the surface, the larvae again appear. They apparently have drifted out with the surface water from the east.

Specific identification of the echinoplutei was not made, but in most samples the larval skeleton was preserved sufficiently to indicate the larval type. Examination of numerous specimens revealed only larvae with fenestrated bars in the post-oral and postero-dorsal arms, and with the body, and recurrent rods forming a calcareous basket similar to the clypeasteroid, *Dendraster excentricus.* The basket, however, appeared to be somewhat more open than in that species from Puget Sound, and the lower ventral transverse rods were not seen, but these rods apparently do not always develop until late in the larval life. The type of bottom occurring in the area of abundant larva is fine sand which is a favourable habitat for sand dollars.

From this survey of echinoplutei in the plankton, it is evident that the shallow waters of the Bering Sea and Alaskan coast must abound in adults of these animals or that the spawning season is especially abrupt and intense during this time of year. The Canadian Arctic Expedition found *Echinorachnicus parma* in water of 24 metres at 59° 24′ N., 165° 11′ W. (Clark, 1920).

The *ophiopluteus larvae* of the brittle stars were more widely distributed, but less abundant, than were the echinoplutei. Like the latter, they were also characteristic of the warmer water of Bering and Chukchi Seas (Figure 6). Concentrations ranging up to 1,515 per haul were found in the region of the Pribilof Islands in 1934. Large numbers were found near Unimak Island in 1947.

It is strikingly noticeable that the ophioplutei, though having their optimum development in rather strongly neritic waters, occurred at 55 per cent of the stations and ranged into areas where few or no larvae of other echinoderms were taken.

Bipinnarian larvae of sea stars were less well represented, but were conspicuous in the plankton from the Pribilof Islands northward along the Alaskan coast to the region of Nome. The largest single catch, 1,030 individuals, was made in 1934 at the entrance to Norton Sound. None was found in the sections with higher salinities and lower temperatures. In 1947 they were poorly represented except at stations N46, N2, and N21 in the regions of Unimak Island, the Pribilof Islands, and Cape Lisburne.

Annelid larvae were found widely distributed in the area. The maximum number caught was at *Chelan* station 30, in Norton Sound, where 10,109 specimens were taken; 9,234 of these were mitraria larvae. Other hauls taken in this same area of diluted warmer water and in the Pribilof Islands regions were rich in annelid larvae. The larvae were absent or only poorly represented in the Siberian waters, and in the section south of St. George Island.

Lamellibranch larvae. The presence of especially large numbers of lamellibranch larvae gave evidence of abundant spawning during both cruises. In 1934, they were found at 82 per cent of the stations and large catches were made especially in the area off Norton Sound to the Siberian coast, and also at the stations to the east and west of St. Paul Island. Smaller catches were made in the narrow portion of Bering

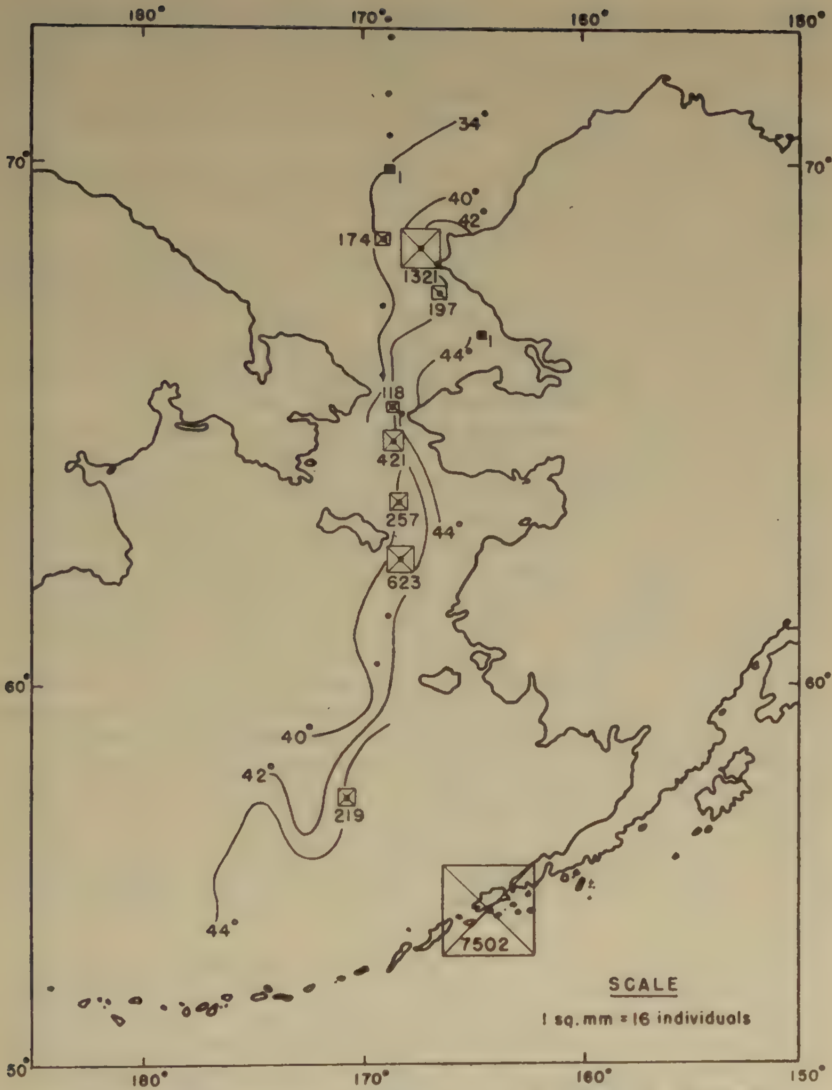

180°
170°
160°
150°
70°
60°
50°
34°
1
40°
42°
174
1321
197
44°
1
118
421
257
44°
623
40°
42°
219
44°
7502
SCALE
1 sq. mm = 16 individuals

FIG. 6.–Ophiopluteus. Numbers per haul, adjusted to 60 metre vertical hauls. The isotherms (Fahrenheit) are for the 25 metre depth. U.S.S. *Nereus*, 1947.

Strait, and in the sections between St. Lawrence, St. Matthew, and Nunivak Islands. In 1947, 95 per cent of the stations yielded larvae, and hauls were especially rich near Unimak Island, and off Norton and Kotzebue Sounds, but considerable numbers were also taken in the open water off Cape Lisburne, and a few occurred clear up to the edge of the Arctic ice.

Though the largest catches were made in the more neritic waters, yet these larvae were less confined to such waters than were any other larvae except barnacle larvae.

Barnacle larvae were well represented over most of the area (Figure 7). In 1934, the greatest concentration was in Bering Strait, and in 1947 it was far to the north at station N15. It is of special interest to note that the chief plankton constituent at station N15 was barnacle larvae, mainly nauplii, but also cyprid stages (Table 1). Other stations in the Chukchi Sea yielded many barnacle larvae.

The occurrence of decidedly greater numbers of barnacle larvae in the northern sections may indicate that the main season of spawning had already taken place in the southern sections before the beginning of the cruise, July 26, and that most of the larvae had assumed the sessile stage or had been sufficiently dispersed to leave the waters only sparsely populated. It is probable that the spawning season progresses gradually northward with the advance of spring and summer. In the San Juan Island region of Puget Sound the height of spawning is in March and April with a temperature range of about 7° to 8·5° C. (Johnson, 1932). Another factor which must necessarily be taken into consideration in the distribution, and concentration of the pelagic larvae of this and other invertebrates is the extent and proximity of suitable substratum for attachment and survival of an extensive community of the adult stages. Much of the Bering Sea area has mud-sand bottom which is unfavourable for attachment.

However, near N15 in the Arctic a rocky area is shown in the *Nereus* chart of the bottom and at N13 a bottom photograph indicates coarse material. Hence, the larvae may have been produced quite locally.

The occurrence of many planktonic larvae of bottom-living animals at the northern stations is of interest, since it is common for many Arctic benthic animals to produce their young fully or nearly developed. In the Arctic barnacles of the genus *Scalpellum*, for example, the larvae are retained in the mantle cavity up to the cyprid stage.

Crab larvae were nowhere abundant, but in 1947 they occurred consistently at nearly all stations northward to N15 but with greatest numbers in the region of Unimak Island and the Pribilofs.

Fish eggs and *larvae* were surprisingly scarce. A few eggs were taken at stations N5 and N22, and larvae at N2.

The *cyphonautes larvae* of Bryozoa, which are so characteristic of neritic plankton farther south, were strangely absent from the catches during both cruises.

Other characteristic plankton animals included the chaetognaths, rotifers, and *Noctiluca*.

Sagitta sp. was most abundant at stations in the Bering Sea, but was distributed all the way to the northernmost station in the Arctic. Both young and adults were present indicating reproduction was taking place especially off the entrance to Norton Sound.

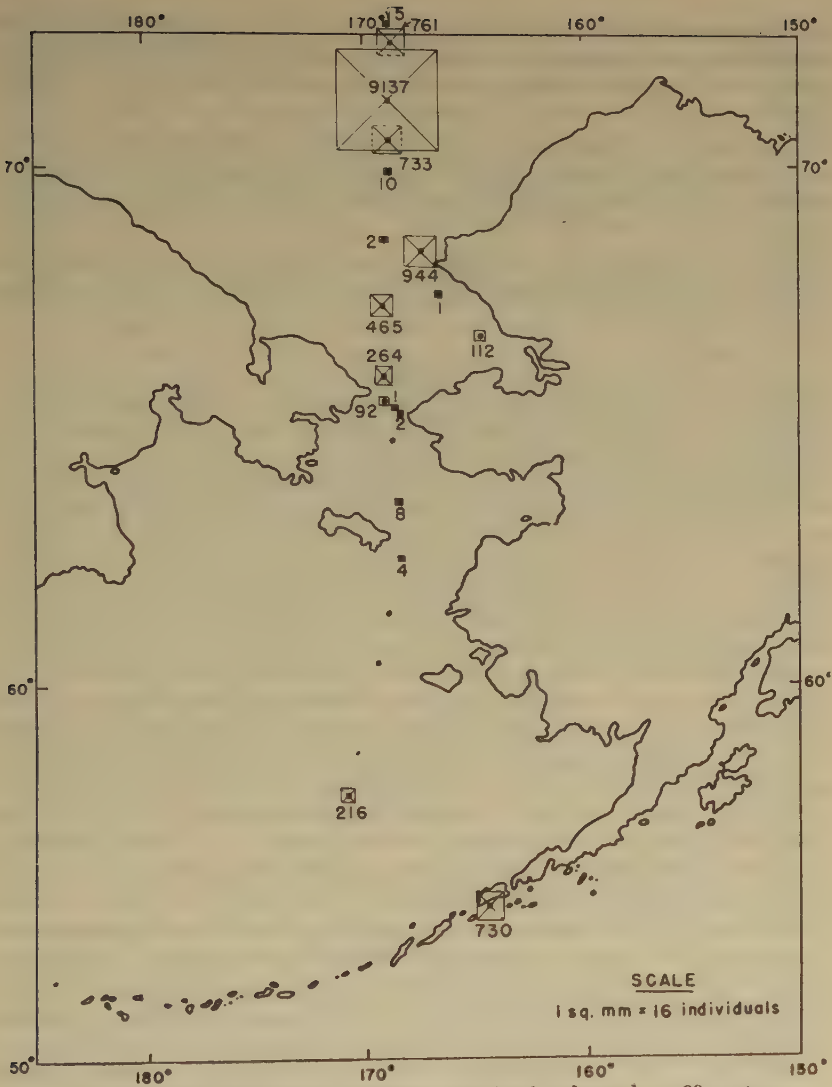

180°
170°
5
761
160°
150°
9137
733
10
70°
70°
2
944
1
465
112
264
1
92
2
8
4
60°
60°
216
730
SCALE
1 sq. mm = 16 individuals
50°
180°
170°
160°
150°

FIG. 7.—Barnacle larvae. Numbers per haul, adjusted to 60 metre vertical hauls, U.S.S. *Nereus*, 1947.

Rotifers were observed only in 1934, and occurred principally near the Pribilofs and Norton Sound. Very few occurred in Bering Strait or at the more westerly stations, and in the section south of St. George Island.

Noctiluca was present only on the Alaskan side in 1934, particularly in the Nome-Norton Sound region. Small numbers were taken at stations in the vicinity of the Pribilofs, and fewer south to the Aleutian Islands.

Podon was taken at nine stations and *Evadne* at four stations in 1934, all in the Nome-Norton Sound area, and in 1947 only at stations N21 and N23.

Discussion

The U.S. Coast Guard cutter *Chelan* carried out hydrographic observations at 120 stations, and the U.S.S. *Nereus* at 39 stations, including those where net hauls were taken.

From the hydrographic reports we learn that in the Bering Sea and Strait and in the Chukchi Sea there is a marked decrease in temperature from east to west during July and August. Along the Alaskan coast to the region of Point Spencer, surface temperatures were above 9° C. In 1934 the 9° isotherm paralleling the coast was situated near the western tip of Nunivak Island, and a tongue of this relatively warm water extended south-westward to include water just to the south of the Pribilof Islands. Along the Siberian coast surface water was from 3° to 6° C., and extended from St. Lawrence Island west of the Diomedes to the Arctic. Subsurface temperatures roughly paralleled the surface isotherms, and also in part the bottom topography. The 6° isotherm at 25 metres and the 9° surface isotherm were in approximately the same positions in much of the area. Between St. Lawrence Island and the Siberian mainland, values below O° C. were found at 25 metres. The isotherms for 25 metre depths are shown in Figures 1 and 6 and for the surface in Figure 4.

In integrating the study, we see that in general the distribution of zooplankton is closely associated with the hydrographic conditions. Thus, also, biologically the area, even in the narrow portion of Bering Strait, can be roughly divided into a western and an eastern section, each with its characteristic community with respect to presence or concentration of either neritic or offshore forms. The eastern neritic community extends westward to include the Pribilof Islands where local production is apparently favoured by the tongue of warm water that enters into the general area. Along the north side of the Aleutian Islands the picture is somewhat confused. The flow of water from the deeper areas permits of no considerable concentration of strictly neritic forms except in the immediate vicinity of the Aleutian Islands and we find an admixture of the relatively more deep water, open sea forms *Calanus tonsus*, *Metridia lucens*, and *Eucalanus bungii*.

Unfortunately, no 1934 net samples are available for the stations midway between St. Paul and Nunivak Islands, but at the latter island there was present a typical inshore community, with a large number of temporary pelagic larvae of echinoderms and annelids, and such pelagic copepods as *Tortanus discaudatus*, and *Epilabidocera amphitrites*. This community persists along the Alaskan coast. Westward from Nunivak Island, however, the neritic element dropped off sharply before reaching the cold waters around St. Matthew Island. At that island was found a very sparse plankton population of a few forms more or less common to both areas, but none of the species common on the Alaskan coast were taken. Here, too, the hydrography offers a probable explanation. St. Matthew Island occupies a position nearly as favourable as the Pribilof Islands with respect to distance from shores producing a strong neritic plankton community, and with respect to surrounding area of shoal water. The critical difference appears to be associated with the direction of prevailing currents and source of water bathing the islands. At St. Matthew Island the currents bring cold water from the west, and probably tend to carry away much of the local production, without replacing it with an incoming supply. The whole section from St. Matthew to St. Lawrence Island was also a barren one at the season of sampling. The plankton community occurring between St. Lawrence Island and Siberia, and along the Siberian side of Bering Strait included the same offshore copepods as were found between the Aleutian Islands and the Pribilofs (Figures 1 and 4). The areas off the Siberian coast are supplied with cold water flowing from the deeper more open sea lying to the south-west.

Some of the coastal community forms may be dispersed by the northward set of the current through Bering Strait along the Alaskan coast, and, thus, reach latitudes unusually high for the species. This is illustrated by the northward extension of *Eucalanus bungii* and *Acartia clausii*, and possibly *Epilabidocera amphitrites*, and others.

The zooplankton distribution indicated by these surveys portrays only the conditions at the prevailing August temperatures. Higher temperatures over a wider area would doubtless favour a wider production and distribution of the neritic forms, for the salinities appear to be favourable over much of the area where depths are relatively shallow.

Sewell (1948) is of the opinion that Arctic species are carried southward through the Bering Strait, but there is no evidence of this during the summer months when the currents appear to flow persistently northward through the Bering Strait.

For a full understanding of the direction of dispersal of the Boreal-Arctic species of the Pacific it will be necessary to have more detailed information on the direction of flow of water through the Bering Strait, especially during seasons other than summer.

SUMMARY

1. Analysis was made of net plankton from 102 stations occupied in 1934, and 21 occupied in 1947, extending from the Aleutian Islands into the Arctic to the edge of the ice pack.
2. Hydrographic observations during the summer reveal the presence of relatively dilute warm water in the eastern section of the Bering Sea and Bering Strait. Along the Alaskan coast the current has a northerly set, and the same is true along the Siberian coast. The flow is stronger and the waters are colder and more saline on the Siberian side of the Bering Strait.
3. Correlated with the hydrographical features, the zooplankton study indicates (1) a western community, characterized by offshore deep-water species, such as *Calanus tonsus*, *Calanus crista-*

tus, Eucalanus bungii bungii, and *Metridia lucens,* and by a relative absence of temporary plankton; and (2) an eastern neritic community, characterized by neritic or estuarine forms, such as *Tortanus discaudatus, Epilabidocera amphitrites, Eurytemora herdmani* and temporary larval stages of littoral invertebrates.

4. The offshore community extends somewhat eastward just north of the Aleutian Islands, and northward through the Bering Strait on the Siberian side.
5. The neritic community includes the Pribilofs and Nunivak Island, and the coast of Alaska. Alaskan neritic forms are apparently carried through Bering Strait along the eastern side, and thus may reach latitudes usually high for the species. The more offshore forms are carried into the Arctic through the western part of the Strait.
6. The large numbers of larvae of benthic animals, especially echinoderms, lamellibranchs, and barnacles gave evidence of abundant spawning in mid-summer clear up into the Arctic Ocean.

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DISCUSSION

Professor Yonge stated that the capture of larvae, but not the adult forms, was quite usual, even in places so thoroughly investigated as Plymouth, e.g. many *Squilla* larvae had been taken, but adults were very rare. He asked Dr. Johnson whether any molluscan larvae had been collected. Dr. Johnson in reply said that pelecypod larvae were concentrated in a line from Alaska past St. Lawrence Island to the Siberian coast. Distribution of these larvae did not conform to that of other larvae taken. It was of interest that the walrus comes down past St. Lawrence Island, indicating that there are probably many bivalves in this area. Professor Yonge said that bivalves near Greenland nearly all have a direct development and provide another example that the proportion of directly developing forms becomes higher in the higher latitudes. Miss Allen asked if any larval squids were taken. Dr. Johnson replied that none were found, but sampling was not satisfactory for swimming forms, e.g. few Euphausiids were captured, although they must have been present. Dr. Hubbs said that the sampling given in this paper was made during a period of ameliorated climate. The conditions were probably different when ice used to come down to the Pribilof Islands. Apparently there is now a northward movement of plankton which may not have occurred at that time. He suggested that the salmon, lamprey, and other forms may also now go further north. Miss Pope asked if the genera of barnacles had been determined. Dr. Johnson replied this had not yet been completed. Professor Yonge asked the depth of attachment of the barnacles. Dr. Johnson stated that this was approximately 30-40 metres. Dr. Hubbs mentioned that on the West Coast they were much deeper.

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Spectral Response of a Quadratic Device to Non-Gaussian Noise*

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(Received February 17, 1954)

In order to compute the spectral response of a quadratic device to noise, a fourth-order moment P of the input noise is sufficient, P being a function of three independent time delays. The function P_1 by which this fourth moment for a non-Gaussian noise differs from the corresponding moment for a Gaussian noise having the same spectrum is examined. The Fourier transform of this function is Q_1, a function of three frequencies. Q_1 is capable of an interpretation in terms of nonlinear correlations between noise components at different frequencies. A specialization of Q_1 leads to E, a function of two frequencies which is a measure of the correlation between the squares of the envelopes associated with those frequencies.

Several networks involving quadratic nonlinear elements are examined to illustrate the theory. It is shown that while the function P makes it possible to compute the complete spectral response of the network, the function E (together with the spectrum of the input) is sufficient in order to find the spectral density at zero frequency. Finally, for three examples of non-Gaussian processes, the corresponding P_1, Q_1 and E functions are computed.

I. INTRODUCTION

HE now-famous theorem of Wiener[1] and Khintchine[2] which relates the autocorrelation and spec- n of a time series enables one to describe analytically spectral response of a linear device to a noise input. of this technique has led to the solution of a large ber of problems in communication and information ry.[3,4] However, there are many situations in com- ications engineering—and in particular in the de- ion of weak signals in noise[5]—which involve rectifi- on of noise, and when this is the case, the auto- elation function of the input *may* not contain suffi- t information to permit one to predict the spectrum e output. When the rectification involved consists ly of squaring or of cross-multiplying, it will be presently that a fourth-order moment of the input e serves this purpose. But first it is desirable to ent definitions and background material on noise lems.

y "noise" will be meant a real, stationary, random,[6,7] tochastic[2] process; i.e., an ensemble of time series governed by the set of probability densities

$$W_1[x_1],$$
$$W_2[x_1,x_2;t_2-t_1],$$
$$\vdots$$
$$W_n[x_1,\cdots,x_n;t_2-t_1,\cdots,t_n-t_{n-1}],$$
$$\vdots$$

where $W_1[x_1]dx_1$ is the probability of finding $x(t_1)$ between x_1 and x_1+dx_1; $W_2[x_1,x_2;t_2-t_1]dx_1dx_2$ is the probability of finding $x(t_1)$ between x_1 and x_1+dx_1, and $x(t_2)$ between x_2 and x_2+dx_2; $\cdots$; $W_n[x_1,\cdots,x_n;t_2-t_1,\cdots,t_n-t_{n-1}]dx_1\cdots dx_n$ is the probability of finding: $x(t_1)$ between x_1 and x_1+dx_1; $\cdots$; and $x(t_n)$ between x_n and x_n+dx_n. Note that the probability density associated with a set of points $t_1,\cdots,t_n$ is a function of the differences $t_2-t_1,\cdots,t_n-t_{n-1}$ and not of the absolute positions of the points on the t axis; this is a consequence of the stationary character of x. The process will be assumed to satisfy the ergodic hypothesis which says, in effect, that the probability densities associated with the ensemble are identical with the probability densities associated with a single typical function.[8] For example, the mean m may be defined either as the mathematical expectation of $x(t)$ for fixed t and over different functions x,

$$m=\mathcal{E}\{x(t)\}\equiv\int_{-\infty}^{\infty}x_1W_1[x_1]dx_1, \tag{1}$$

or as $x(t)$ for a particular function x averaged over t,

$$m=\langle x(t)\rangle\equiv\lim_{T\to\infty}(1/2T)\int_{-T}^{T}x(t)dt. \tag{1.1}$$

The autocorrelation function $R(\tau)$ is defined by

$$\begin{aligned}R(\tau)&=\mathcal{E}\{[x(t)-m][x(t-\tau)-m]\}\\&=\langle[x(t)-m][x(t-\tau)-m]\rangle.\end{aligned} \tag{2}$$

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his work represents one of the results of research carried out r contract with the Bureau of Ships, Navy Department.

n leave of absence from the Marine Physical Laboratory of Scripps Institution of Oceanography of the University of rnia.

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We shall assume $R(\tau)$ to be integrable;‡ it has as its Fourier transform the (uniformly) continuous function $S(\omega)$,

$$S(\omega)=\int_{-\infty}^{\infty} R(\tau)e^{-i\omega\tau}d\tau,$$
$$R(\tau)=(1/2\pi)\int_{-\infty}^{\infty} S(\omega)e^{i\omega\tau}d\omega, \qquad (3)$$

where $S(\omega)$, according to the Wiener-Khintchine theorem, is the power spectrum of $x(t)$.

If $u(t)$ is the result of an "operation" on $x(t)$, e.g.,

$$\text{(i)} \qquad u(t)=\int_{-\infty}^{\infty} a(\sigma)x(t-\sigma)d\sigma, \qquad (4)$$

where $a(t)$ is an integrable function of time,§

(ii) $u(t)=[x(t)]^r$,

(iii) $u(t)=(d/dt)x(t)$, etc.,

$u(t)$ will be another stochastic process and very often it is in theory possible to compute the probability densities associated with u from a knowledge of those associated with x.[9] However, this approach is far too general to be feasible in very many cases, and in practi one is usually content to predict to only a limited exte the behavior of the output, e.g., to predict its first-ord probability density and/or power spectrum.

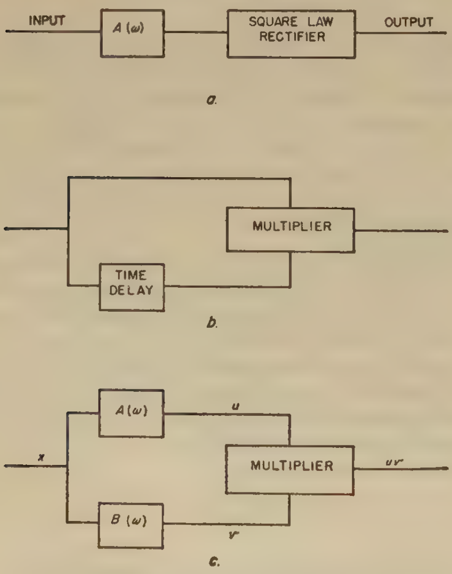

FIG. 1. Elementary quadratic devices.

There are two important classes of problems whic fall into the latter category and which have been su cessfully attacked; *viz*, problems in which (a) the oper tion is linear, or (b) the noise is Gaussian. If the oper tion is linear [as in Eq. (4)], then regardless of tl other statistics of $x(t)$, $S_u(\omega)$, the spectrum of u, related to the spectrum of x by

$$S_u(\omega)=S(\omega)|A(\omega)|^2, \qquad ($$

where

$$A(\omega)=\int_{-\infty}^{\infty} a(t)e^{-i\omega t}dt, \qquad ($$
$$a(t)=(1/2\pi)\int_{-\infty}^{\infty} A(\omega)e^{i\omega t}d\omega.$$

On the other hand, if the noise $x(t)$ is Gaussian, i.e if W_n is the nth-order normal distribution,[10] then tl statistics of x (and very often the statistics of u) a completely determined by the autocorrelation fun tion of x.[11–13]

The problem which we have set out to investigate the determination of the spectrum of the output of quadratic device when the input is a (possibly) no Gaussian noise. We use the term "quadratic device" mean an electronic network in which there is a quadrat operation, either square law rectification or cros multiplication, which may be preceded and/or followe by linear operations. Block diagrams of some quadrat networks are shown in Fig. 1. Consider in particul the network shown in Fig. 1c (the networks in Fig 1a, 1b, being but special cases of that shown in 1c where $A(\omega)$ and $B(\omega)$ represent real linear filters an $u(t)$ and $v(t)$ their respective outputs when the inpu is $x(t)$. Then $w(t)=u(t)v(t)-\langle uv\rangle$ has autocorrelation

$$\langle w(t)w(t-\tau)\rangle=\int\int_{-\infty}^{\infty}\int\int d\sigma_1\cdots d\sigma_4 a(\sigma_1)b(\sigma_2)a(\sigma_3)b(\sigma$$
$$\times[\langle x(t-\sigma_1)x(t-\sigma_2)x(t-\tau-\sigma_3)x(t-\tau-\sigma_4)\rangle$$
$$-\langle x(t-\sigma_1)x(t-\sigma_2)\rangle\langle x(t-\sigma_3)x(t-\sigma_4)\rangle], \qquad ($$

$a(t)$ and $b(t)$ being the time responses of filters $A($ and $B(\omega)$. Thus, in order to compute this *second*-ord moment of w, one needs a *fourth*-order moment of This is characteristic of problems involving quadrat devices and provides the motivation for this paper.

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‡ Throughout this paper, "integrable" will mean the function belongs to both L_1 and L_2; see N. Wiener, *The Fourier Integral* (Dover Publications, New York).

§ This operation will be referred to hence as "linear filtering." The filter will be called real or complex according as $a(t)$, the time response of the filter to a δ-function input (see reference 7, p. 30), is real or complex. The filter is realizable only if $a(t)$ vanishes for negative argument (see reference 4, p. 12).

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II. A FOURTH-ORDER MOMENT

he noise function will be represented by the real hastic process $x(t)$ for which the moments

$$\langle x(t)\rangle=0,$$

$$\langle x(t)x(t-\tau)\rangle=R(\tau), \tag{8}$$

$$\langle x(t)x(t-\tau_1)x(t+\tau_2)x(t+\tau_3)\rangle=P(\tau_1,\tau_2,\tau_3)$$

. It is with the function $P(\tau_1,\tau_2,\tau_3)$ that we shall nost concerned in this section. By (a) rearranging factors of the fourth moment occurring in Eq. (8) (b) translating along the time axis, one can show P satisfies certain relations of the form

) $$P(\tau_1,\tau_2,\tau_3)=P(\tau_1,\tau_3,\tau_2)$$
$$=P(-\tau_2,-\tau_1,\tau_3), \tag{9}$$

) $$P(\tau_1,\tau_2,\tau_3)=P(-\tau_1,\tau_1+\tau_2,\tau_1+\tau_3).$$

addition, we have (c) that the mechanism generat- :(t) is isotropic in time, then

) $$P(\tau_1,\tau_2,\tau_3)=P(-\tau_1,-\tau_2,-\tau_3); \tag{10}$$

last condition will not generally be fulfilled, ver.

nsider next the function $P_1(\tau_1,\tau_2,\tau_3)$ defined by quation

$$,\tau_2,\tau_3)=R(\tau_1)R(\tau_2-\tau_3)+R(\tau_2)R(\tau_3+\tau_1)$$
$$+R(\tau_3)R(\tau_1+\tau_2)+P_1(\tau_1,\tau_2,\tau_3). \tag{11}$$

reader will recognize $P-P_1$ as the corresponding h moment when x is a Gaussian time series. Thus, restrict our attention to moments of order no r than four, P_1 is a measure of the "non-Gaussian- ' of the time series. If x has the property that $x(t)$ $x(t-\tau)$ become statistically independent as $|\tau|$ nes large, it will follow that

$$\lim_{s\to\infty}P_1(a_1s+b_1,\ a_2s+b_2,\ a_3s+b_3)=0, \tag{12}$$

l a_i, b_i such that $a_1^2+a_2^2+a_3^2>0$ (i.e., $P_1\to 0$ along inear path). We shall make the further assumption P_1 goes to zero sufficiently rapidly to make it an rable function. Then it will possess a Fourier form Q_1:

$$,\omega_2,\omega_3)=\int\!\!\int_{-\infty}^{\infty}\!\!\int P_1(\tau_1,\tau_2,\tau_3)$$
$$\times e^{-(\omega_1\tau_1+\omega_2\tau_2+\omega_3\tau_3)}d\tau_1 d\tau_2 d\tau_3, \tag{13}$$

$$,\tau_2,\tau_3)=(1/2\pi)^3\int\!\!\int_{-\infty}^{\infty}\!\!\int Q_1(\omega_1,\omega_2,\omega_3)$$
$$\times e^{i(\omega_1\tau_1+\omega_2\tau_2+\omega_3\tau_3)}d\omega_1 d\omega_2 d\omega_3.$$

The function Q_1 is real when $x(t)$ is isotropic in time; for, denoting the complex conjugate with a bar, we have

$$\bar{Q}_1(\omega_1,\omega_2,\omega_3)=\int\!\!\int\!\!\int_{-\infty}^{\infty}\!\!\int P_1(\tau_1,\tau_2,\tau_3)$$
$$\times e^{i(\omega_1\tau_1+\omega_2\tau_2+\omega_3\tau_3)}d\tau_1 d\tau_2 d\tau_3$$
$$=\int\!\!\int_{-\infty}^{\infty}\!\!\int P_1(-\tau_1,-\tau_2,-\tau_3)$$
$$\times e^{-i(\omega_1\tau_1+\omega_2\tau_2+\omega_3\tau_3)}d\tau_1 d\tau_2 d\tau_3 \tag{14}$$
$$=\int\!\!\int_{-\infty}^{\infty}\!\!\int P_1(\tau_1,\tau_2,\tau_3)$$
$$\times e^{-i(\omega_1\tau_1+\omega_2\tau_2+\omega_3\tau_3)}d\tau_1 d\tau_2 d\tau_3$$
$$=Q_1(\omega_1,\omega_2,\omega_3).$$

It is clear now that both second- and fourth-order statistics of x are specified when P is given; for,

$$R(\tau)=\lim_{s\to\infty}P(0,s,s-\tau)/R(0)$$

and

$$R^2(0)=\lim_{s\to\infty}P(0,s,s). \tag{15}$$

The effect produced on $P(\tau_1,\tau_2,\tau_3)$ by passing $x(t)$ through a real filter may be deduced as follows: if $u(t)$ is related to $x(t)$ according to Eq. (4) with $a(t)$ real, then the new fourth moment is

$$P_u(\tau_1,\tau_2,\tau_3)=\langle u(t)u(t-\tau_1)u(t+\tau_2)u(t+\tau_3)\rangle$$
$$=\int\!\!\int\!\!\int_{-\infty}^{\infty}\!\!\int d\sigma_1\cdots d\sigma_4 a(\sigma_1)\cdots a(\sigma_4)$$
$$\times\langle x(t-\sigma_1)x(t-\sigma_2-\tau_1)x(t-\sigma_3+\tau_2)$$
$$\times x(t-\sigma_4+\tau_3)\rangle$$
$$=R_u(\tau_1)R_u(\tau_2-\tau_3)+R_u(\tau_2)R_u(\tau_3+\tau_1)$$
$$+R_u(\tau_3)R_u(\tau_1+\tau_2)+P_{u1}(\tau_1,\tau_2,\tau_3), \tag{16}$$

where

$$R_u(\tau)=\int_{-\infty}^{\infty}\!\!\int a(\sigma_1)a(\sigma_2)R(\sigma_1-\sigma_2-\tau)d\sigma_1 d\sigma_2, \tag{17}$$

and

$$P_{u1}(\tau_1,\tau_2,\tau_3)=\int\!\!\int\!\!\int_{-\infty}^{\infty}\!\!\int d\sigma_1\cdots d\sigma_4 a(\sigma_1)\cdots a(\sigma_4)$$
$$\times P_1(\sigma_2-\sigma_1+\tau_1,\ \sigma_1-\sigma_3+\tau_2,\ \sigma_1-\sigma_4+\tau_3). \tag{18}$$

In the frequency domain, the formulas corresponding to Eqs. (17) and (18) are Eq. (5) and

$$Q_{u1}(\omega_1,\omega_2,\omega_3)$$
$$=Q_1(\omega_1,\omega_2,\omega_3)\bar{A}(\omega_1)A(\omega_2)A(\omega_3)A(\omega_3+\omega_2-\omega_1). \tag{19}$$

The most important property of Q_1 has yet to be stated; meanwhile it is instructive both for the sake of completeness and also in order to provide a model for later calculations to include a proof of the statement which will be referred to in this paper as the Wiener-Khintchine theorem.

Wiener-Khintchine Theorem. The autocorrelation function and power spectrum of a stochastic process form a Fourier pair.

Proof: Consider a family of complex, ideal band-pass filters $G_\alpha(\omega)$,

$$\begin{aligned} G_\alpha(\omega) &= 1, \quad |\omega-\omega_2| \leqq \Delta/2 \\ &= 0 \quad \text{otherwise}, \end{aligned} \tag{20}$$

where ω_α ranges over the entire frequency axis and $\omega_{-\alpha} = -\omega_\alpha$. Let $\xi_\alpha(t)$ denote the (complex) output of $G_\alpha(\omega)$ when the input is $x(t)$:

$$\xi_\alpha(t) = \int_{-\infty}^{\infty} g_\alpha(\sigma)x(t-\sigma)d\sigma, \tag{21}$$

where

$$g_\alpha(t) = (1/2\pi)\int_{-\infty}^{\infty} G_\alpha(\omega)e^{i\omega t}d\omega. \tag{22}$$

Note that since $g_{-\alpha}(t) = \bar{g}_\alpha(t)$, $\xi_{-\alpha}(t) = \bar{\xi}_\alpha(t)$. Now let $\xi_1(t)$ and $\xi_2(t)$ be a pair of $\xi_\alpha(t)$ and consider the product

$$\xi_1(t)\bar{\xi}_2(t) = \iint_{-\infty}^{\infty} g_1(\sigma_1)\bar{g}_2(\sigma_2)x(t-\sigma_1)x(t-\sigma_2)d\sigma_1 d\sigma_2. \tag{23}$$

The time average of this expression is

$$\langle \xi_1\bar{\xi}_2 \rangle = \iint_{-\infty}^{-\infty} g_1(\sigma_1)\bar{g}_2(\sigma_2)R(\sigma_1-\sigma_2)d\sigma_1 d\sigma_2; \tag{24}$$

letting $S(\omega)$ be *defined* by Eq. (3), the above expression may be transformed to

$$\langle \xi_1\bar{\xi}_2 \rangle = (1/2\pi)\int_{-\infty}^{\infty} S(\omega)G_1(\omega)\bar{G}_2(\omega)d\omega. \tag{24.1}$$

Hence, from the nature of the $G_\alpha(\omega)$ and from the uniform continuity of $S(\omega)$, we have

(i) for sufficiently small Δ, $\langle \xi_1\bar{\xi}_2 \rangle = 0$ when $\omega_1 \neq \omega_2$,

(ii) $\langle |\xi_1|^2 \rangle = S(\omega_1')(\Delta/2\pi)$, where $\omega_1 - \Delta/2 \leqq \omega_1' \leqq \omega_1 + \Delta/2$,

or

$$\begin{aligned} &\text{(i}'\text{)} \qquad \lim_{\Delta\to 0}(2\pi/\Delta)\langle \xi_1\bar{\xi}_2 \rangle = 0, \quad \omega_1 \neq \omega_2. \\ &\text{(ii}'\text{)} \qquad \lim_{\Delta\to 0}(2\pi/\Delta)\langle |\xi_1|^2 \rangle = S(\omega_1), \end{aligned} \tag{25}$$

the limit being approached uniformly in ω_1. Since $\langle |\xi_1|^2 \rangle$ is a measure of the power of $x(t)$ contained between the frequencies $\omega_1 - \Delta/2$ and $\omega_1 + \Delta/2$, $\lim_{\Delta\to 0}(2\pi/\Delta)\langle |\xi_1|^2 \rangle$ yields the power density at the frequency ω_1, q.e.d.

The remainder of this section is devoted to a theorem involving fourth moments which is analogous to the W-K theorem for second moments. Let $\xi_1(t), \cdots, \xi_4(t)$ be the (complex) outputs of four filters $G_1(\omega), \cdots, G_4(\omega)$ [as in Eq. (20)] with center frequencies $\omega_1, \cdots, \omega_4$, when the common input is $x(t)$. Take the product

$$\begin{aligned} \bar{\xi}_1(t)\xi_2(t)\xi_3(t)\bar{\xi}_4(t) = \iiiint_{-\infty}^{\infty} d\sigma_1 \cdots d\sigma_4 \\ \times \bar{g}_1(\sigma_1)g_2(\sigma_2)g_3(\sigma_3)\bar{g}_4(\sigma_4) \\ \times x(t-\sigma_1)x(t-\sigma_2)x(t-\sigma_3)x(t-\sigma_4), \end{aligned} \tag{26}$$

and average

$$\begin{aligned} \langle \bar{\xi}_1\xi_1\xi_3\bar{\xi}_4 \rangle = \iiiint_{-\infty}^{\infty} d\sigma_1 d\sigma_2 d\sigma_3 d\sigma_4 \\ \times \bar{g}_1(\sigma_1)g_2(\sigma_2)g_3(\sigma_3)\bar{g}_4(\sigma_4) \\ \times P(\sigma_1-\sigma_4, \sigma_4-\sigma_2, \sigma_4-\sigma_3). \end{aligned} \tag{27}$$

If one now substitutes

$$\begin{aligned} P(\sigma_1-\sigma_4, \sigma_4-\sigma_2, \sigma_4-\sigma_3) = R(\sigma_1-\sigma_2)R(\sigma_3-\sigma_4) \\ + R(\sigma_1-\sigma_3)R(\sigma_2-\sigma_4) + R(\sigma_1-\sigma_4)R(\sigma_2-\sigma_3) \\ + P_1(\sigma_1-\sigma_4, \sigma_4-\sigma_2, \sigma_4-\sigma_3), \end{aligned} \tag{28}$$

the integral may be separated into two parts: the first, I_1 involving the R's and the second, I_2, involving P_1.

The first integral is simply

$$\begin{aligned} I_1 = \langle \bar{\xi}_1(t)\xi_2(t)\rangle\langle \xi_3(t)\bar{\xi}_4(t)\rangle + \langle \bar{\xi}_1(t)\xi_3(t)\rangle\langle \xi_2(t)\bar{\xi}_4(t)\rangle \\ + \langle \bar{\xi}_1(t)\bar{\xi}_4(t)\rangle\langle \xi_2(t)\xi_3(t)\rangle. \end{aligned} \tag{29}$$

The second integral may be transformed to

$$\begin{aligned} I_2 &= (1/2\pi)^3 \iiint_{-\infty}^{\infty} Q_1(\lambda_1,\lambda_2,\lambda_3)\bar{G}_1(\lambda_1)G_2(\lambda_2)G_3(\lambda_3) \\ &\qquad \times \bar{G}_4(\lambda_3+\lambda_2-\lambda_1)d\lambda_1 d\lambda_2 d\lambda_3 \\ &= (1/2\pi)^3 \iiint_{\omega_i-\Delta/2}^{\omega_i+\Delta/2} Q_1(\lambda_1,\lambda_2,\lambda_3) \\ &\qquad \times G_4(\lambda_3+\lambda_2-\lambda_1)d\lambda_1 d\lambda_2 d\lambda_3. \end{aligned} \tag{30}$$

As the Fourier transform of an integrable function Q_1 is uniformly continuous; this permits the representation

$$\begin{aligned} I_2 = (1/2\pi)^3 Q_1(\omega_1', \omega_2', \omega_3') \\ \times \iiint_{\omega_i-\Delta/2}^{\omega_i+\Delta/2} G_4(\lambda_3+\lambda_2-\lambda_1)d\lambda_1 d\lambda_2 d\lambda_3, \end{aligned} \tag{30.1}$$

where $\omega_i-\Delta/2\leqq\omega_i'\leqq\omega_i+\Delta/2$, $i=1, 2, 3$. Thus we see that

(i) for sufficiently small Δ, I_2 vanishes unless

$$\omega_4=\omega_3+\omega_2-\omega_1; \tag{31}$$

(ii) when Eq. (31) is satisfied, the triple integral occurring in Eq. (30.1) may be evaluated as $2\Delta^3/3$, leading to

$$I_2=2/3(\Delta/2\pi)^3Q_1(\omega_1',\omega_2',\omega_3'). \tag{30.2}$$

These results may be incorporated into

Theorem

(i) $\lim\limits_{\Delta\to 0}(2\pi/\Delta)^3\langle\bar{\xi}_1\xi_2\xi_3\bar{\xi}_4\rangle=0$ when $\omega_4\neq\omega_3+\omega_2-\omega_1$.

(ii)
$$\begin{aligned}\lim_{\Delta\to 0}(2\pi/\Delta)^3\{\langle\bar{\xi}_1\xi_2\xi_3\bar{\xi}_4\rangle-\langle\bar{\xi}_1\xi_2\rangle\langle\xi_3\bar{\xi}_4\rangle\\ -\langle\bar{\xi}_1\xi_3\rangle\langle\xi_2\bar{\xi}_4\rangle-\langle\bar{\xi}_1\bar{\xi}_4\rangle\langle\xi_2\xi_3\rangle\}\\ =2/3Q_1(\omega_1,\omega_2,\omega_3),\end{aligned} \tag{32}$$

when Eq. (31) is satisfied, the limit being approached uniformly in ω_1, ω_2, ω_3.

III. THE ENVELOPE CORRELATION FUNCTION

The concept of the envelope and phase of a stationary time series has been given precise meaning in a recent paper of Bunimovitch.[14] His approach may be outlined as follows: given $x(t)$, a real stationary time series, one can form a new time series $y(t)$ which will be in "quadrature" with $x(t)$ by performing on the latter the "Hilbert" transformation,

$$y(t)=\lim_{T\to\infty}(1/\pi)\int_{-T}^{T}[x(t-\sigma)/\sigma]d\sigma. \tag{33}$$

Then $X(t)=x(t)+iy(t)$ is a complex time series for which the spectrum is, for positive argument, proportional to the spectrum of x, while for negative argument it is zero. If $X(t)$ is put into polar form $X(t)=\rho(t)\exp i\theta(t)$, $\rho(t)$ is by definition the "envelope" and $\theta(t)$ the "phase" of the original time series and

$$\begin{aligned}x(t)&=\rho(t)\cos\theta(t),\\ y(t)&=\rho(t)\sin\theta(t).\end{aligned} \tag{34}$$

Let us now define

$$x_\alpha(t)=\xi_\alpha(t)+\bar{\xi}_\alpha(t), \tag{35}$$

where $\xi_\alpha(t)$ is as defined in Sec. II; $x_\alpha(t)$ may also be identified with the output of a *real* ideal band-pass filter $H_\alpha(\omega)$,

$$\begin{aligned}H_\alpha(\omega)&=1,\quad |\omega\pm\omega_\alpha|\leqq\Delta/2,\\ &=0\quad \text{otherwise,}\end{aligned} \tag{36}$$

when the input is $x(t)$. Then $2\xi_\alpha(t)$ and $x_\alpha(t)$ bear the same relation to one another as $X(t)$ and $x(t)$, above. Accordingly, $2|\xi_\alpha(t)|$ is the envelope of the time series $x_\alpha(t)$.

By combining Eqs. (25) and (32) one can write

$$\langle|\xi_1\xi_2|^2\rangle-\langle|\xi_1|^2\rangle\langle|\xi_2|^2\rangle\doteq 2/3Q_1(\omega_1,\omega_2,\omega_1)(\Delta/2\pi)^3$$

when $\omega_1\neq\omega_2$,

$$\begin{aligned}\langle|\xi_1|^4\rangle-\langle|\xi_1|^2\rangle^2\doteq S^2(\omega_1)(\Delta/2\pi)^2\\ +2/3Q_1(\omega_1,\omega_1,\omega_1)(\Delta/2\pi)^3.\end{aligned} \tag{37}$$

Thus one sees that the function $Q_1(\omega_1,\omega_2,\omega_1)$ may be interpreted as a measure of the correlation between the squares of the envelopes of $x_1(t)$ and $x_2(t)$. It is for this reason that the (real, continuous) function

$$E(\omega_1,\omega_2)\equiv Q_1(\omega_1,\omega_2,\omega_1)=Q_1(\omega_1,\omega_1,\omega_2), \tag{38}$$

will be referred to hence as the "envelope correlation function" of the time series $x(t)$. Clearly, $E(\omega_1,\omega_2)=E(\omega_2,\omega_1)=E(-\omega_1,\omega_2)$. Note that both E and Q_1 are "densities" in that each must be multiplied by the third power of band width in order to have physical significance.

If $x(t)$ is passed through a (real) linear filter of admittance $A(\omega)$, the output $u(t)$ will have envelope correlation function [see Eq. (19)]

$$E_u(\omega_1,\omega_2)=E(\omega_1,\omega_2)|A(\omega_1)A(\omega_2)|^2. \tag{39}$$

It is possible to express $D(\tau_1,\tau_2)$, the Fourier transform of $E(\omega_1,\omega_2)$, in terms of the function $P_1(\tau_1,\tau_2,\tau_3)$ in the following manner:

$$\begin{aligned}D(\tau_1,\tau_2)&=(1/2\pi)^2\iint_{-\infty}^{\infty}E(\omega_1,\omega_2)e^{i(\omega_1\tau_1+\omega_2\tau_2)}d\omega_1d\omega_2\\ &=(1/2\pi)^2\iiint_{-\infty}^{\infty}ds_1ds_2ds_3\\ &\quad\times\iint_{-\infty}^{\infty}d\omega_1d\omega_2P_1(s_1,s_2,s_3)\\ &\quad\times\exp i(\omega_1\tau_1+\omega_2\tau_2-\omega_1s_1-\omega_2s_2-\omega_1s_3)\\ &=\int_{-\infty}^{\infty}P_1(s,\tau_2,\tau_1-s)ds.\end{aligned} \tag{40}$$

It is important to point out here that $E(\omega_1,\omega_2)$ is *not* a correlation density in the strict sense of the word; indeed, if one divides Eq. (37) by $(\Delta/2\pi)^3$ and takes the limit as $\Delta\to 0$, one sees that

$$\begin{aligned}\lim_{\Delta\to 0}(2\pi/\Delta)^3[\langle|\xi_1\xi_2|^2\rangle-\langle|\xi_1|^2\rangle\langle|\xi_2|^2\rangle]\\ =2\pi\delta(\omega_1-\omega_2)S(\omega_1)S(\omega_2)+2/3E(\omega_1,\omega_2).\end{aligned} \tag{37.1}$$

Thus, one must append to $2/3E(\omega_1,\omega_2)$ the function $2\pi\delta(\omega_1-\omega_2)S(\omega_1)S(\omega_2)$ in order to make it a correlation density. Consequently, E should not be expected to possess all of the properties of such a function. For example, E need not be positive definite: we have in Example 2 of Sec. V an instance in which $E(\omega_1,\omega_1)$ is negative for some ω_1.

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[14] V. I. Bunimovitch, J. Tech. Phys. (U.S.S.R.) 19, 1231 (1949).

Unlike the function $Q_1(\omega_1,\omega_2,\omega_3)$, the envelope correlation function is capable of a description in terms of limits of mean products of outputs of *real* ideal band-pass filters. For, if $H_1(\omega)$ and $H_2(\omega)$ are two such filters [as in Eq. (36)] with center frequencies ω_1 and ω_2 and if $x_1(t)$ and $x_2(t)$ are their respective outputs when the inputs are $x(t)$, then

Corollary

$$\text{(i)}\quad \lim_{\Delta\to 0}(2\pi/\Delta)^3[\langle x_1^2x_2^2\rangle-\langle x_1^2\rangle\langle x_2^2\rangle] =8/3E(\omega_1,\omega_2),\quad \omega_1\neq\omega_2. \tag{41}$$

$$\text{(ii)}\quad \lim_{\Delta\to 0}(2\pi/\Delta)^3[\langle x_1^4\rangle-3\langle x_1^2\rangle^2]=4E(\omega_1,\omega_1).$$

Proof of this corollary is effected by a straightforward application of the Theorem, Sec. II, to Eq. (41) when $x(t)$ is as defined in Eq. (35).

IV. APPLICATION TO QUADRATIC DEVICES

As it was demonstrated in Sec. I, in order to determine the spectral response of a quadratic device to a noise input it is necessary to have knowledge not only of the spectrum of the input but also of the P_1 function of the input. It is our intention in this section to show how, given this additional information, one proceeds to calculate the spectrum of the output.

Let us return to the example which was left incomplete in Sec. I. The autocorrelation of $w(t)=u(t)v(t)-\langle uv\rangle$ as given by Eq. (7) may now be rewritten as

$$R_w(\tau)=\int\int\int\int_{-\infty}^{\infty} d\sigma_1\cdots d\sigma_4 a(\sigma_1)b(\sigma_2)a(\sigma_3)b(\sigma_4) \times[R(\sigma_1-\sigma_3-\tau)R(\sigma_2-\sigma_4-\tau) +R(\sigma_1-\sigma_4-\tau)R(\sigma_2-\sigma_3-\tau) +P_1(\sigma_1-\sigma_4-\tau,\ \sigma_4-\sigma_2+\tau,\ \sigma_4-\sigma_3)]. \tag{7.1}$$

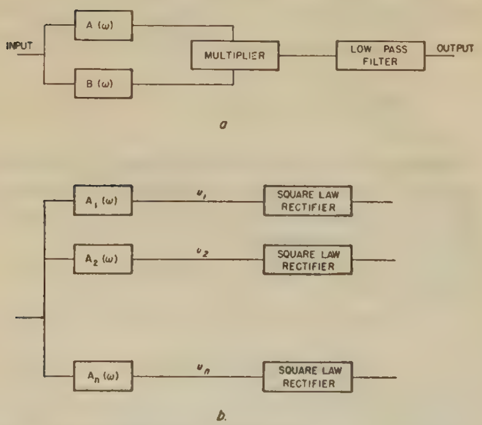

FIG. 2. Additional networks to which the theory may be applied.

The spectrum of w is obtained by taking the Fourier transform,

$$S_w(\omega)=\int_{-\infty}^{\infty} R_w(\tau)e^{-i\omega\tau}d\tau$$

$$=(1/2\pi)\int_{-\infty}^{\infty} S(\omega_1)S(\omega_1+\omega)[|A(\omega_1)B(\omega_1+\omega)|^2 +\bar{A}(\omega_1)B(\omega_1)B(\omega_1+\omega)\bar{A}(\omega_1+\omega)]d\omega_1 +(1/2\pi)^2\int\int_{-\infty}^{\infty} Q_1(\omega_1,\ \omega_1+\omega,\ \omega_2) \times\bar{A}(\omega_1)A(\omega_2)B(\omega_1+\omega)\bar{B}(\omega_2+\omega)d\omega_1d\omega_2. \tag{42}$$

It is of interest to set $\omega=0$ in Eq. (42) and obtain

$$S_w(0)=(1/2\pi)\int_{-\infty}^{\infty} S^2(\omega_1)[|A(\omega_1)B(\omega_1)|^2 +\bar{A}(\omega_1)^2B^2(\omega_1)]d\omega_1+(1/2\pi)^2\int\int_{-\infty}^{\infty} E(\omega_1,\omega_2) \times\bar{A}(\omega_1)A(\omega_2)B(\omega_1)\bar{B}(\omega_2)d\omega_1d\omega_2. \tag{42.1}$$

This result is of use when the quadratic operation is followed by low pass filtering (or averaging) as shown in Fig. 2a; when this is the case, the spectral density at zero frequency of the output of the quadratic element often contains sufficient information regarding the noise, since the higher frequency fluctuations are suppressed.[5,15] The fact that Q_1 may be replaced by E not only simplifies considerably the formula, but also exhibits another important property of the envelope correlation function.

In the problem of the detection of signals in noise, networks such as shown in Fig. 2b are sometimes employed.[15] Without going into the details of the detection problem, we can still investigate how our theory applies to such circuitry. The device consists of N real operations performed in parallel on the common input $x(t)$:

$$u_n(t)=\int_{-\infty}^{\infty} a_n(\sigma)x(t-\sigma)d\sigma, \tag{43}$$

where

$$a_n(t)=(1/2\pi)\int_{-\infty}^{\infty} A_n(\omega)e^{-i\omega t}d\omega; \tag{44}$$

and

$$w_n(t)=u_n^2(t)-\langle u_n^2\rangle,\quad n=1,\ 2,\ \cdots,\ N. \tag{45}$$

First of all, one can obtain the spectrum of the output w_n of a single "channel" as a special case of Eq. (42):

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[15] Philip Rudnick, J. Appl. Phys. 24, 128 (1953).

$$S_n(\omega)=(1/\pi)\int_{-\infty}^{\infty} S(\omega_1)S(\omega_1+\omega)$$
$$\times|A_n(\omega_1)A_n(\omega_1+\omega)|^2d\omega_1$$
$$+(1/2\pi)^2\int\int_{-\infty}^{\infty} Q_1(\omega_1,\ \omega_1+\omega,\ \omega_2)\bar{A}_n(\omega_1)$$
$$\times A_n(\omega_1+\omega)A_n(\omega_2)A_n(\omega_2+\omega)d\omega_1 d\omega_2. \quad (46)$$

The spectral density at zero frequency is then

$$S_n(0)=(1/\pi)\int_{-\infty}^{\infty} S^2(\omega_1)|A_n(\omega_1)|^4d\omega_1$$
$$+(1/2\pi)^2\int\int_{-\infty}^{\infty} E(\omega_1,\omega_2)$$
$$\times|A_n(\omega_1)A_n(\omega_2)|^2d\omega_1 d\omega_2. \quad (46.1)$$

It is interesting to observe that if $A_n(\omega)$ is a (real) narrow band filter with center frequency ω_n and effective band width Δ (rad/sec), then Eq. (46.1) can be approximated by

$$S_n(0)\doteq 4S^2(\omega_n)|A_n(\omega_n)|^4(\Delta/2\pi)$$
$$+4E(\omega_n,\omega_n)|A_n(\omega_n)|^4(\Delta/2\pi)^2. \quad (46.2)$$

Thus, $S_n(0)$ differs from the value it would have for Gaussian noise $[E(\omega_n,\omega_n)=0]$ by a term which is second order in $\Delta/2\pi$. This is in agreement with the principle which has been stated by Rice,[11] Middleton[13] and others that the statistics of a narrow band of any noise approach Gaussian as the band width approaches zero.

The cross correlation between two outputs w_m and w_n can also be determined:

$$R_{mn}(\tau)=\langle w_m(\tau)w_n(t-\tau)\rangle$$
$$=\int\int\int\int_{-\infty}^{\infty} d\sigma_1\cdots d\sigma_4 a_m(\sigma_1)a_m(\sigma_2)a_n(\sigma_3)a_n(\sigma_4)$$
$$\times[2R(\sigma_1-\sigma_4-\tau)R(\sigma_1-\sigma_3-\tau)$$
$$+P_1(\sigma_1-\sigma_4-\tau,\ \sigma_4-\sigma_2+\tau,\ \sigma_4-\sigma_3)]. \quad (47)$$

The cross spectrum is then

$$S_{mn}(\omega)=\int_{-\infty}^{\infty} R_{mn}(\tau)e^{-i\omega\tau}d\tau$$
$$=(1/\pi)\int_{-\infty}^{\infty} S(\omega_1)S(\omega_1+\omega)\bar{A}_m(\omega_1)$$
$$\times A_m(\omega_1+\omega)A_n(\omega_1)A_n(\omega_1+\omega)d\omega_1$$
$$+(1/2\pi)^2\int\int_{-\infty}^{\infty} Q_1(\omega_1,\ \omega_1+\omega,\ \omega_2)\bar{A}_m(\omega_1)$$
$$\times A_m(\omega_1+\omega)A_n(\omega_2)A_n(\omega_2+\omega)d\omega_1 d\omega_2. \quad (48)$$

The value of the cross spectrum at zero frequency provides a measure of the correlation between the low frequency parts of w_m and w_n and is given by

$$S_{mn}(0)=(1/\pi)\int_{-\infty}^{\infty} S^2(\omega_1)|A_m(\omega_1)A_n(\omega_1)|^2d\omega_1$$
$$+(1/2\pi)^2\int\int_{-\infty}^{\infty} E(\omega_1,\omega_2)$$
$$\times|A_m(\omega_1)A_n(\omega_2)|^2d\omega_1 d\omega_2. \quad (48.1)$$

Note that if A_m and A_n are non-overlapping filters $(A_m(\omega)A_n(\omega)\equiv 0)$, then the correlation between the low frequency parts of w_m and w_n is due entirely to the envelope correlation function.

V. EXAMPLES

Included below are three examples of non-Gaussian processes for which the P_1, Q_1 and E functions have been computed. In each case, statistics of second order—the autocorrelation and spectrum—have been studied already in some detail, but little attention has previously been directed toward fourth-order statistics.

1. Square of a Gaussian Time Series

Let $u(t)$ be a Gaussian time series with first and second moments

$$\langle u(t)\rangle=0,$$
$$\langle u(t)u(t-\tau)\rangle=r(\tau), \quad (49)$$

where for simplicity we demand that $r(\tau)$ be integrable and $r(0)=1$. Then $x(t)=u^2(t)-1$ will be the non-Gaussian noise which we shall examine. This noise could be realized physically by applying, say, "white" thermal noise to a linear filter $A(\omega)$, where $A(\omega)$ is chosen to impart to its output the desired spectral character [see Eq. (5)], and then rectifying quadratically the filter output.

It is well known that

$$R(\tau)=\langle x(t)x(t-\tau)\rangle=2r^2(\tau), \quad (50)$$

but the fourth moment involving x is more difficult to obtain. The method used by the author was to express $\langle x(t)x(t-\tau)x(t+\tau_2)x(t+\tau_3)\rangle$ in terms of 8th-, 6th-, 4th-, and 2nd-order moments of the Gaussian variables $u(t)$, $u(t-\tau_1)$, $u(t+\tau_2)$, $u(t+\tau_3)$, and then to evaluate these moments by differentiating the appropriate characteristic function.[10] One is thus led to the result

$$P_1(\tau_1,\tau_2,\tau_3)=16[r(\tau_1)r(\tau_1+\tau_2)r(\tau_2-\tau_3)r(\tau_3)$$
$$+r(\tau_2)r(\tau_2-\tau_3)r(\tau_3+\tau_1)r(\tau_1)$$
$$+r(\tau_3)r(\tau_3+\tau_1)r(\tau_1+\tau_2)r(\tau_2)]. \quad (51)$$

P_1 is clearly integrable and has as its Fourier transform the (real, non-negative) function

$$Q_1(\omega_1,\omega_2,\omega_3)=16(1/2\pi)\times\int_{-\infty}^{\infty}[s(\lambda)s(\lambda+\omega_1)s(\lambda+\omega_2)s(\lambda+\omega_2+\omega_3)+s(\lambda)s(\lambda+\omega_2)s(\lambda+\omega_3)s(\lambda+\omega_3+\omega_1)+s(\lambda)s(\lambda+\omega_3)s(\lambda+\omega_1)s(\lambda+\omega_1+\omega_2)]d\lambda, \quad (52)$$

where

$$s(\omega)=\int_{-\infty}^{\infty}r(\tau)e^{-i\omega\tau}d\tau. \quad (53)$$

The envelope correlation function is then

$$E(\omega_1,\omega_2)=16(1/2\pi)\int_{-\infty}^{\infty}[2s(\lambda)s^2(\lambda+\omega_1)s(\lambda+\omega_1+\omega_2)+s(\lambda)s(\lambda+\omega_1)s(\lambda+\omega_2)s(\lambda+\omega_1+\omega_2)]d\lambda, \quad (54)$$

and

$$(1/2\pi)^2\int\int_{-\infty}^{\infty}E(\omega_1,\omega_2)d\omega_1d\omega_2=16\int_{-\infty}^{\infty}[2r^2(\tau)+r^4(\tau)]d\tau>0. \quad (55)$$

2. Random Telegraph Signal[11,16]

Let $x(t)$ be either $+1$ or -1 so that it is of the form of a flat top wave. Let the zero crossings be distributed along the t axis in such a manner that the probability of a crossing between t and $t+dt$ is (in the limit) equal to μdt and is independent of what happens outside the interval $(t, t+dt)$. It is known then that

$$R(\tau)=e^{-2\mu|\tau|}, \quad (56)$$

and an extension of the type of argument which leads to Eq. (56) will show

$$P_1(\tau_1,\tau_2,\tau_3)=-[g_1(\tau_1,\tau_2,\tau_3)+g_2(\tau_1,\tau_2,\tau_3)+g_3(\tau_1,\tau_2,\tau_3)], \quad (57)$$

where

$$\begin{aligned}
&\qquad\qquad\qquad\text{except when}\\
g_1&=e^{-2\mu[|\tau_1|+|\tau_2-\tau_3|]}\begin{cases}\tau_2,\tau_3>0,\ \tau_1>-\min(\tau_2,\tau_3)\\ \tau_2,\ \tau_3<0,\ \tau_1<\min(-\tau_2,\ -\tau_3),\end{cases}\\
g_2&=e^{-2\mu[|\tau_2|+|\tau_3+\tau_1|]}\begin{cases}\tau_1>0,\ \tau_3<0,\ \tau_2>-\min(\tau_1,\ -\tau_3)\\ \tau_1<0,\ \tau_3>0,\ \tau_2<\min(-\tau_1,\ \tau_3),\end{cases}\\
g_3&=e^{-2\mu[|\tau_3|+|\tau_1+\tau_2|]}\begin{cases}\tau_1>0,\ \tau_2<0,\ \tau_3>-\min(\tau_1,\ -\tau_2)\\ \tau_1<0,\ \tau_2>0,\ \tau_3<\min(-\tau_1,\ \tau_2).\end{cases}
\end{aligned} \quad (58)$$

The functions g_i are all integrable and possess Fourier transforms which, combined, yield

$$Q_1(\omega_1,\omega_2,\omega_3)=-(1/2\mu)^3\times[24+4(\lambda_1^2+\lambda_2^2+\lambda_3^2+\lambda_4^2)-8\lambda_1\lambda_2\lambda_3\lambda_4]/(1+\lambda_1^2)(1+\lambda_2^2)(1+\lambda_3^2)(1+\lambda_4^2), \quad (59)$$

where (1) $\omega_4=\omega_3+\omega_2-\omega_1$ and (2) $\lambda_i=\omega_i/2\mu$. The envelope correlation function is then

$$E(\omega_1,\omega_2)=-(1/2\mu)^3\times[24+8(\lambda_1^2+\lambda_2^2-\lambda_1^2\lambda_2^2)]/(1+\lambda_1^2)^2(1+\lambda_2^2)^2; \quad (60)$$

note that $E(\omega_1,\omega_1)$ is negative when $\lambda_1^2<3$.

3. The Shot Effect[11]

Let

$$u(t)=\sum_{\nu=-\infty}^{\infty}f(t-\tau_\nu), \quad (61)$$

where $f(t)$ is a real valued, integrable function and where the epochs τ_ν are randomly and independently distributed in time with density μ; then $x(t)=u(t)-\mathcal{E}\{u\}$ will be the non-Gaussian process to be examined.

Using Middleton's[17] generalization of the Campbell theorem, it can be shown that the characteristic function of any finite set of $u_\lambda\equiv u(t_\lambda)$, $\lambda=1, 2, \cdots N$, is

$$\phi_N(\eta_1,\cdots,\eta_N)=\mathcal{E}\{\exp[i\sum_{\lambda=1}^{N}u_\lambda\eta_\lambda]\}=\exp\left\{\mu\int_{-\infty}^{\infty}\{\exp[i\sum_{\lambda=1}^{N}\eta_\lambda f(t+t_\lambda)]-1\}dt\right\},\quad N=1, 2, \cdots. \quad (62)$$

This system of equations completely defines u (and subsequently x) as a stochastic process, and moments involving the u_λ may be computed by differentiating ϕ_N as in Example 1.

For example,

$$R(\tau)=\mu\int_{-\infty}^{\infty}f(t)f(t-\tau)dt, \quad (63)$$

and

$$S(\omega)=\mu|F(\omega)|^2, \quad (64)$$

where

$$F(\omega)=\int_{-\infty}^{\infty}f(t)e^{-i\omega t}dt. \quad (65)$$

The P_1 function is

$$P_1(\tau_1,\tau_2,\tau_3)=\mu\int_{-\infty}^{\infty}f(t)f(t-\tau_1)f(t+\tau_2)f(t+\tau_3)dt, \quad (66)$$

and its transform is

$$Q_1(\omega_1,\omega_2,\omega_3)=\mu\bar{F}(\omega_1)F(\omega_2)F(\omega_3)\bar{F}(\omega_3+\omega_2-\omega_1). \quad (67)$$

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[16] G. W. Kenrick, Phil. Mag. (January, 1929).

[17] D. Middleton, J. Appl. Phys. 22, 1143 (1951).

The envelope correlation function is[‖]

$$\begin{aligned} E(\omega_1,\omega_2) &= \mu|F(\omega_1)F(\omega_2)|^2 \\ &= S(\omega_1)S(\omega_2)/\mu. \end{aligned} \tag{68}$$

It is of interest to allow the density of pulses μ to increase while keeping the total power in x constant: let

$$x_\mu(t)=\sum_\nu f_\mu(t-\tau_\nu)-\mathcal{E}\{\sum_\nu f_\mu\}, \tag{69}$$

where $f_\mu(t)=f(t)/\sqrt{\mu}$. The spectrum of x_μ is

$$S_\mu(\omega)=|F(\omega)|^2, \tag{70}$$

while

$$Q_{\mu 1}(\omega_1,\omega_2,\omega_3)=F(\omega_1)F(\omega_2)F(\omega_3)\bar{F}(\omega_3+\omega_2-\omega_1)/\mu. \tag{71}$$

Thus we see that as $\mu\rightarrow\infty$, S_μ remains fixed while $Q_{\mu 1}\rightarrow 0$; or, insofar as fourth-order statistics are concerned, x_μ becomes Gaussian.

ACKNOWLEDGMENT

The significance of fourth-order moments in the analysis of non-Gaussian noises was first brought to the author's attention by Professor Carl Eckart, and it was at the latter's suggestion that this investigation was originally begun. The author is also indebted to other members of the laboratory staff, and in particular to Dr. Philip Rudnick, for providing indispensable help and encouragement.

[‖] Note the non-negative character of E. This is a fundamental property of processes which can be represented by Eq. (61).

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IRON IN MARINE WATERS

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IRON IN MARINE WATERS[1]

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ABSTRACT

The soluble and particulate iron in marine waters of the North Pacific were determined spectrophotometrically by utilizing the iron complexes of alpha, alpha-bipyridyl and bathophenanthroline. Particulate iron is defined as that iron which was retained by a molecular filter, the soluble iron as that which passed through the molecular filter. The soluble iron in surface and deep waters varied but slightly about 3.4 g/L. The particulate iron gave a value of 4.5 g/L. in waters deeper than 500 m, but in shoaler depths it was oftimes higher and showed a large amount of scatter. The high surface values are related to the turnover of iron by the members of the marine biosphere.

INTRODUCTION

The iron in marine waters is intimately involved in two of the primary problems of oceanography, sedimentation and productivity. Although thousands of analyses on iron have been published (Table I), a number of questions concerning its biogeochemical cycle and the results thereof remain unanswered. Analyses in the deep sea have been rare; only four out of 39 investigators have obtained samples from depths greater than 1,000 m. This is rather appalling since more than 90% of the oceanic waters lie deeper than 1,000 m.

Cooper (1948) catalogued ten forms of iron within sea water. Experimentally, however, it is difficult to quantitatively assay more than two forms, the soluble and particulate iron. Further, the distinction between these two types is arbitrarily dependent upon the porosity of the filter utilized for the separation.

With the recent availability of membrane filters (Goldberg, Baker and Fox, 1952) which rapidly pass water through their pores and which have a known porosity, it has become possible to delimit "particulate iron" by particle size. With the "Millipore Type HA" filters used in this investigation, iron particles 0.5 μ or greater were retained on the membrane; these will be designated as "particulate iron." The iron not retained by the filter will be classified as "soluble iron."

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The influence of growth processes on the seasonal distribution of iron in the oceans has been observed in only one investigation (Thompson and Bremner, 1935). The fact that plankton utilize only particulate iron (Goldberg, 1952; Allen and Nelson, 1910; Harvey, 1937) focuses attention on the solid phases of iron in the sea.

In order to investigate the distribution of iron in deeper oceanic water as well as in the upper layers, analyses for particulate iron have been made for a number of stations in the northern Pacific Ocean. Since most of the iron in the sea is particulate, the inhomogeneity of the distribution invites a statistical analysis of the data.

ANALYTICAL METHODS

Two reagents, each involving the formation of an intensely red-colored complex with ferrous iron, are well suited to an analysis of iron in marine waters. α, α-bipyridyl was initially used by Cooper (1937) in an investigation of iron in English Channel waters; a modification

TABLE I. Iron Determination in Marine Waters

Northeast Atlantic

Location	*Method*	*Depth (meters)*	*Fe in mg/L*	
			Soluble	*Total*
1.* Mediterranean	Vol. a.	I	—	2.0
2. English Channel	?	?	—	0.10
3. Irish Sea	Vol. a.	?	—	3.25
4. English Channel	Col. a.	70	—	0.10
5. English Channel	?	0–68	0.003 –0.006	—
6. Tropical N. Atlantic (Meteor Profiles 12, 13, 14)	?	—	—	0.06
7. Norwegian Sea	Col. b.	0–400	0.0049	0.0085
8. Barents Sea	Col. b.	?	—	0.010– 0.020
9. North Atlantic	Col. b.	?	—	0.003– 0.011 (Surface 0.013– 0.014 (Bottom)
10. English Channel	Col. c.	0–70	0.007	0.014
11. Swedish Coast	Spectr.	?	—	0.008
12. English Channel	Col. d.	0–120	0.000	0.020
Northwest Atlantic				
13. Gulf of Maine	Col. b.	1–340	—	0.019
14. U. S. Coast	Col. b.	0–3830	0.005	0.021
15. U. S. Coast	Col. e.	Surface	0.003	—

* See page 185 for references used in this table.

TABLE I—Continued

			Depth	*Fe in mg/L*	
	Location	*Method*	*(meters)*	*Soluble*	*Total*
	NORTHEAST PACIFIC				
16.	Washington Coast	Col. b.	0–300	—	0.073
17.	Coasts of U. S. A., Canada, Alaska	Col. b.	0–2000	0.026	0.091
	NORTHWEST PACIFIC				
18.	Seto Inland Sea	?	0–27	—	0.145
19.	Ryukyu Island	?	0–200	—	0.138
20.	Osaka-Wan Inland Sea	?	0–65	—	0.060
21.	Osaka-Wan, Osaka	?	0–10	—	0.083
22.	Seto-Naikai (Inland Sea)	?	0–150	—	0.333
23.	Kyushu Island	?	0–100	—	0.146
24.	Osaka-Wan	?	0–16	—	0.089
25.	Saruga-Wan, Honshu, Japan	?	0–978	—	0.027
26.	Osaka-Wan, Osaka	?	0–7	—	0.372
27.	Osaka Bay (off Osaka)	?	Surface	—	0.091
28.	Seto Inland Sea	?	0–33	—	0.046
29.	East China Sea (Kyushu Inlets)	?	0–68	—	0.024
30.	Sea of Japan (Fukuoka, Kyushu)	?	0–20	—	0.009
31.	Sea of Japan (Maizura Bay, Honshu)	?	0–30	—	0.212
32.	Southern Japan (Open Ocean)	?	0–1009	—	0.010
33.	Southern Japan (Osaka Bay, Kii Suido)	?	0–75	—	0.033
34.	Southern Japan (Kii Suido)	?	0–70	—	0.009
35.	Seto Inland Sea	?	0–49	—	0.069
36.	Northern Japan (Muroran Harbor, Hokkaido)	Col. b.	0–12.5	—	0.810
37.	Northern Japan (Muroran Harbor, Hokkaido)	Col. b.	0–12.5	—	0.310
38.	Off SE. Honshu and S. Shikoku	Col. d.	0–1554	—	0.0095
	ALL OCEANS				
39.		?	?	—	1.5

Methods: Vol. a. Titration with $KMnO_4$ after $CaCO_3$ or $Mg\ (OH)_2$ precipitation. Col. a. Ferrocyanide development with ferric iron. Col. b. Thiocyanate development with ferric iron. Col. c. Tripyridyl development with ferrous iron. Col. d. Bipyridyl development with ferrous iron. Col. e. o-phenanthroline development with ferrous iron.

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of this method was adopted for our spectrophotometric determinations where quantities between 0 and 100 γ per sample were encountered. The procedure is simple and rapid, but the probable error becomes large for samples containing less than 5 γ. The colored complex is stable for at least a year in the pH range of 2.0 to 7.0.

Bathophenanthroline (4, 7-diphenyl 1, 10-phenanthroline) was used for analyses of iron samples in the concentration range below the sensitivity of bipyridyl. The method was first described by Smith, et al. (1952) for the determination of iron in raw and treated municipal water supplies and later by Peterson (1953) for the determination of serum iron. Although the method is more laborious than the bipyridyl procedure because of an extraction of the ferroin complex with isoamyl alcohol, it can be used with reasonable accuracy for total quantities of iron as small as 0.30 γ.

In the determination of particulate iron, approximately one liter of sea water was filtered per sample in order to obtain on the filter membrane a quantity adequate for use of the bipyridyl reagent. However, the soluble iron could not be readily concentrated in a simple manner, and consequently it was necessary to use the more sensitive bathophenanthroline method.

Comparison of α, α-bipyridyl and bathophenanthroline was made by analyzing ten different samples of particulate iron by both methods. For iron concentrations of 30 γ/L, the average difference in results by the two methods was 1.6 γ/L. Although the low concentration of soluble iron made it impossible to make such a direct comparison, there is no reason to believe that the soluble iron values determined by bathophenanthroline are invalid. A thorough investigation by Smith showed no interfering ions if the pH is properly adjusted. Further evidence of the adaptability of this reaction is found in the fact that the molar extinction coefficient in sea water is the same as that in distilled water.

The oxidation process for the release of particulate organic iron by perchloric acid was tested with five samples of hemin. The average recovery was 97%.

The bipyridyl method for particulate iron was adapted for routine use aboard ship. Reagent concentrations were adjusted so that 1.0 ml dispensers could be used for each reagent with the exception of $HClO_4$ which required a 5.0 ml dispenser. A transite hood containing electrical heaters specifically constructed to fit 30 ml Kjeldahl flasks was installed for the oxidation process. In the shore laboratory much less elaborate equipment suffices; Pyrex test tubes heated on a sand bath are satisfactory.

REAGENTS

(1) *0.001 M bathophenanthroline.* Dissolve 0.0334 g of reagent in 50 ml of ethanol and 50 ml of water.

(2) *α, α-bipyridyl.* Dissolve 0.40 g of reagent in 100 ml of 0.2 N HCl.

(3) *10% hydroxylamine hydrochloride.* Doubly recrystallized Reagent Grade salt contains traces of iron. Dissolve 10 g of this salt in 90 ml of water and add 4 ml of Reagent (1) above. Extract the ferroin complex into two successive 10 ml portions of isoamyl alcohol and repeat this process until no further red color appears with the addition of Reagent (1). This latter procedure removes the final traces of iron.

(4) *Glacial acetic acid.* Reagent Grade.

(5) *50% sodium acetate.* To 50 g of Reagent Grade salt in 50 ml of water add 2 ml of Reagent (3) and 4 ml of Reagent (1). Extract with isoamyl alcohol until a red color ceases to appear

in the alcohol layer. If copper is present, a yellow color appears in neutral or basic solution. This does not interfere in the iron determinations, but copper should be removed since it may reduce the availability of bathophenanthroline to the ferrous ion.

(6) *Isoamyl-alcohol.* Reagent Grade or redistilled Technical Grade.

(7) *1.2 N HCl.* Dilute 10 ml of concentrated Reagent Grade HCl to 100 ml.

(8) *70% perchloric acid.* Reagent Grade perchloric acid contains small quantities of iron, about 1.4×10^{-1} γ/ml. Since purification is impractical, this iron must be taken into account in the reagent blank.

(9) *Standard ferric iron solution.* To obtain a solution containing 400 γ of ferric iron/ml, dissolve 0.3455 g of $Fe(NH_4)(SO_4)_2 \cdot 12\,H_2O$ in 100 ml of iron free water with 1.6 ml of concentrated HCl added. 10 ml of this solution are diluted to 100 ml and 1000 ml to give working standards for the bipyridyl and bathophenanthroline methods respectively.

DETERMINATION OF PARTICULATE IRON WITH α, α-BIPYRIDYL

Sample Analysis. Measured samples of approximately 1.2 l, collected in Nansen bottles, were passed through a membrane filter, after which the membrane was placed in a 30 ml Vycor Kjeldahl flask containing 5 ml of perchloric acid. Heat was applied until no further evolution of acid fumes was observed. When cooled, 1 ml of 1.2 N HCl and 10 ml of water were added, after which the contents were transferred to a 50-ml glass stoppered graduated cylinder. The flask was rinsed with two 10 ml portions of water. The combined solutions were treated with 1 ml each of hydroxylamine hydrochloride, sodium acetate, and bipyridyl solutions. After the sample was diluted to 50 ml, its optical density was determined in 10 cm cells in a Beckman DU Spectrophotometer at 522 mμ.

Standardization Curves. 0.00, 0.20, 0.40, 0.60, 0.80, and 1.00 ml volumes of the standard ferric solution containing 40 γ/ml were treated with 1 ml each of 1.2 N HCl, sodium acetate, hydroxylamine and bipyridyl solutions; each solution was then diluted to volume in a 50 ml flask. The optical density was determined as above. Beer's Law curves are easily reproduced to within 2%.

Reagent Blanks. If the reagent solutions are properly purified, the only extraneous iron comes from the perchloric acid and the filter membrane. A large number of membranes from several different packages were analyzed and were found to average 2.0 γ of iron per membrane with a standard deviation of 2.0 γ. Since there is a variation from one package to another, the reagent blank was determined for each package by assaying several pads.

DETERMINATION OF SOLUBLE IRON WITH BATHOPHENANTHROLINE

Sample Analysis. Five ml of 70% perchloric acid were added to 100 ml of filtered sea water in a Pyrex or Vycor Kjeldahl flask, and the solution was evaporated until the sea salt formed a thin paste. Care was taken not to evaporate to bone dryness, since this gave low results, probably from the formation of difficultly-soluble iron oxides. The residue, dissolved in 100 ml of water, was heated to boiling.

After the solution cooled to room temperature, 2 ml of hydroxylamine hydrochloride were added, and the pH was adjusted to 4.0 by the addition of 0.4 ml of glacial acetic acid and 50% sodium acetate. The required quantity of sodium acetate depended upon the amount of $HClO_4$ retained in the sea salt.

Following buffering, 4.0 ml of bathophenanthroline reagent were added, and the colored complex was extracted with 20 ml of isoamyl alcohol. Two extractions with 10 ml of alcohol proved adequate. The alcohol was transferred to a 25 ml volumetric flask and diluted to volume. In most cases it was difficult to prevent a few small drops of salt water from entering the flask, but these settled to the bottom and caused no interference. The transmission was then determined in a 10 cm cell at 533 mμ.

Standardization Curves. Because the extinction coefficient of the bathophenanthroline complex is not affected by the presence of sea salt in the aqueous sample, it was not necessary to use sea water in the standardization analyses.

To 100 ml portions of water in 125 ml separatory funnels were added respectively 0.00, 0.30, 0.60, 0.90, 1.20 and 1.50 ml of a ferric iron standard containing 4.00 γ/ml. The samples were treated with 1.0 ml glacial HAc, 0.85 ml of 50% sodium acetate, 2.0 ml of 10% hydroxylamine hydrochloride, and 4.0 ml of bathophenanthroline. After extraction with two 10 ml portions of isoamyl alcohol, the extract was diluted to 25.0 ml in a volumetric flask with redistilled ethanol. The samples were read in the spectrophotometer as above.

Reagent blanks. These values were determined by evaporating 5.0 ml of 70% $HClO_4$ until only a small fraction of a milliliter remained in the flask. Subsequent processing was identical with that used for the sea water samples.

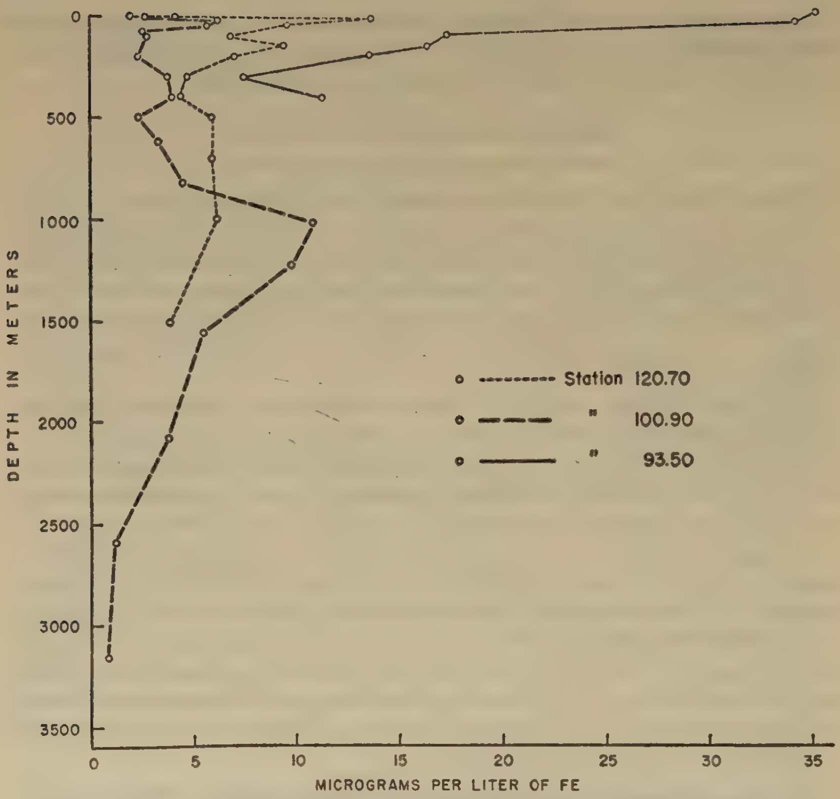


Figure 1. Vertical distribution of particulate iron off the California coast.

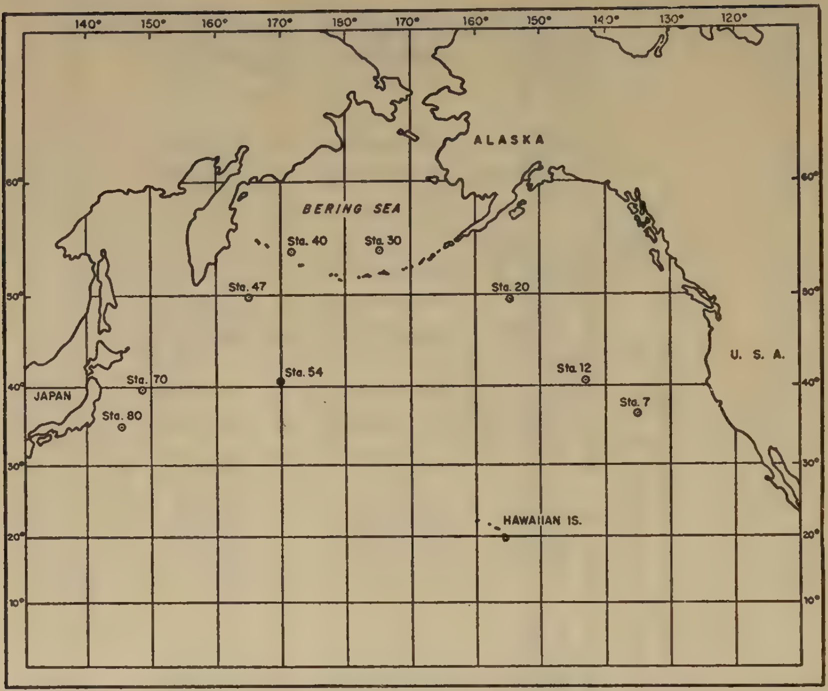
RESULTS

Initially, particulate iron analyses were made off the coast of California. Typical data are shown graphically in Fig. 1. The results indicated a decided concentration of iron in the upper water masses. Further, replicate analyses showed poor agreement, sometimes differing by factors as high as five. To determine whether or not this observed variation was significant and to study the variation in samples from the same depth, a set of experiments was devised to make the results amenable to statistical analysis (Dixon and Massey, 1951).

Clusters of three Nansen bottles per depth (5 m apart, the minimum safe working distance) were arranged for each station in order to study the variation at a given depth. Ten depths ranging from the surface to 3500 m were taken. Nine stations were made on the 1953

TABLE II. IRON ANALYSES TRANS-PACIFIC EXPEDITION
PARTICULATE IRON IN μG/L

Nominal Depth	*Station 7*	*Station 12*	*Station 20*	*Station 30*	*Station 40*	*Station 47*	*Station 54*	*Station 70*	*Station 80*
	36°21.8′N	40°26.9′N	49°29.5′N	53°57.7′N	53°57.0′N	49°50.1′N	40°34.5′N	39°44.0′N	35°04.5′N
	134°53.0′W	143°32.0′W	154°56.5′W	175°04.5′W	171°10.8′E	165°49.2′E	170°02.3′E	148°24.0′E	145°07.5′E
10	36, 37, 34	14, 10, 8	6, 6, 6	2, 5, 14	0, 3, 13	0, 0, 1	0, 4, 6	4, 0, 1	0, 5, 3
50	23, 29, 50								
100	35, 14, 28	20, 20, 16	11, 13, 11	6, 1, 3	11, 10, 15	0, 0, 0	3, 1, 14	1, 4, 0	0, 2, 0
200	27, 24, 32	15, 12, 5	17, 9, 8	5, 7, 12	7, 8, 2	0, 1, 6	0, 0, 4	1, 8, 1	3, 13, 19
300	15, 16, 31	6, 4, —	4, 1, 7	6, 9, 2	0, 0, 9	0, 0, 0	6, 0, 6	1, 2, 1	0, 0, 5
400		11 — —	10, 7, 29	3, 7, 8	6, 8, 16	3, 4, 0	4, 2, 6	1, 0, 0	0, 0, 6
500	30, 10, 11	5, 5, 3	6, 4, 5	5, 5, 6	2, 0, 11	1, 2, 0	1, 5, 0	1, 0, 9	2, 5, 2
700	13, 10, 16								
1000	14, 13, 26	5, 6, 5	3, 3, 10	4, 5, 4	0, 1, 3	2, 3, 11	3, 0, 1	0, 1, 0	2, 0, 1
1500	17, 10, 17								
2000	14, 11, 15	8, 8, 3	3, 6, 4	4, 15, 2	4, 12, 7	10, 8, 4	2, 1, 1	4, 1, 1	0, 0, 12
3000		2, 2, 4	2, 16, 2	5, 16, 7	0, 6, 17	5, 11, 14	9, 11, 5	5, 1, 2	0, 1, 0
3500		5, 9, 7	4, 6, 10	7, 5, 5	5, 3, 0	3, 1, 2	1, 1, 11	0, 0, 0	2, 0, 1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Sta. 40
Sta. 30
Sta. 47
Sta. 20
Sta. 54
Sta. 12
Sta. 7
Sta. 70
Sta. 80
JAPAN
U. S. A.
HAWAIIAN IS.

Figure 2. Station positions on the Trans-Pacific expedition of the Scripps Institution of Oceanography, 1953.

Trans-Pacific Expedition of the Scripps Institution of Oceanography (Fig. 2) (Wooster, 1954), and the results are given in Tables II and III.

An analysis of variance was made for each station to ascertain if the surface and deep populations were significantly different (Table IV). Stations 7, 12, 20 and 47 evince discrete populations at the two levels, 0 to 400 and 500 to 3500 m, whereas no statistical difference exists in the other five stations.

An intercomparison of the surface and deeper waters between stations is presented in Table V. Station 7 is markedly different from all other stations in both of its distinct populations. Station 47, with a notable absence of iron in the upper layers, appears unique. The data also emphasize the fact that the deeper waters show less variation between populations than the surface values. The analysis of variance of the iron populations for a given station shows that the variation within a cluster is as great as the variation between clusters.

TABLE III. SUMMARY OF TABLE II.
PARTICULATE IRON FROM TRANS-PACIFIC STATIONS

	0–400 m av.		*500–3500 m av.*		*Av. of all depths*	
Station	γ/L	*Std. Dev.*	γ/L	*Std. Dev.*	γ/L	*Std. Dev.*
7*	27	11	17	6	23	10
12	12	5	5	2	8	5
20	10	7	6	4	8	6
30	6	4	6	4	6	4
40	7	5	5	5	7	5
47	1	2	5	4	3	4
54	4	4	4	4	4	4
70	2	2	2	3	2	2
80	4	6	2	3	3	5

* Upper layer depth range 0–300 m; deep water layer 500–2000 m.

TABLE IV. ANALYSIS OF VARIANCE FOR COMPARISON OF PARTICULATE IRON IN THE UPPER (0–400 m) LAYER WITH THAT IN THE DEEP WATER (500–3500 m). DATA FROM TRANS-PACIFIC EXPEDITION.

Station		*Sums of Squares*	*Degrees of Freedom*	*Variance*	*F ratio*
7*	Between Layers	1526	1	1526	24.2
	Within Layers	1761	28	63	
12	Between Layers	293	1	293	18.7
	Within Layers	393	25	16	
20	Between Layers	124	1	124	4.27
	Within Layers	813	28	29	
30	Between Layers	1	1	1	0.07
	Within Layers	409	28	15	
40	Between Layers	51	1	51	1.82
	Within Layers	785	28	28	
47	Between Layers	136	1	136	11.5
	Within Layers	328	28	12	
54	Between Layers	0.2	1	0.2	0.01
	Within Layers	407	28	15	
70	Between Layers	0.2	1	0.2	0.04
	Within Layers	158	28	5.6	
80	Between Layers	26	1	26	1.29
	Within Layers	566	28	20	

* Upper layer depth range 0–300 m; deep water layer 500–2000 m. Critical F_{99}—7.64 except for Station 12, where F_{99} is 7.82. Critical F_{95}—4.20 except for Station 12, where F_{95} is 4.26.

Eight samples of water collected from the Scripps Pier at La Jolla as well as duplicate samples of bottom water collected from two locations in the open Pacific Ocean were passed through a molecular filter for an analysis of the soluble iron. The results are given in

TABLE V. F RATIOS FOR INTERCOMPARISON OF TRANS-PACIFIC EXPEDITION STATIONS

UPPER LAYER (0–400 m)

Station	*12*	*20*	*30*	*40*	*47*	*54*	*70*	*80*
7*	32	40	78	61	126	93	105	80
12	—	0.8	11	4.7	50	21	43	14
20	—	—	3.5	1.3	25	9.2	20	7.1
30	—	—	—	0.5	22	2.8	15	1.7
40	—	—	—	—	18	4.2	13	3.0
47	—	—	—	—	—	7.3	1.5	3.9
54	—	—	—	—	—	—	3.5	0.0
70	—	—	—	—	—	—	—	1.8
80	—	—	—	—	—	—	—	—

DEEP WATER (500–3500 m)

Station	*12*	*20*	*30*	*40*	*47*	*54*	*70*	*80*
7*	39	24	24	27	28	42	65	60
12	—	0.1	1.1	0.1	0.0	2.0	16	11
20	—	—	0.3	0.3	0.1	2.2	11	6.0
30	—	—	—	1.0	0.8	4.0	15	11.9
40	—	—	—	—	4.1	0.6	4.2	3.3
47	—	—	—	—	—	0.9	6.0	4.7
54	—	—	—	—	—	—	2.2	1.5
70	—	—	—	—	—	—	—	0.1

* Upper layer 0–300 m; Deep water 500–2000 m. F_{99} critical values are 7.64 for all station comparisons except those involving Station 12, in which case F_{99} is 7.82. F_{95} critical values are 4.20 for all station comparisons except those involving Station 12, in which case F_{95} is 4.26.

TABLE VI. SOLUBLE IRON CONTENT OF SEA WATER

Sea Water Sample	*γ/L Soluble Iron*
La Jolla, California	4.1
	4.1
	3.6
	2.0
	3.3
	5.2
	3.3
	0.7
Mean	3.3
Bottom Water (4000 m) 12°S; 129°W.	2.6 5.5
Bottom Water (4500 m) 11°S; 134°W.	2.6 3.9
Mean	3.7
Grand Mean	3.4

Table VI. Mean values for the two groups of samples are 3.3 and 3.7 μg/L respectively, with an over-all average of 3.4 μg/L. This compares favorably with the soluble iron concentrations found previously as given in Table I with the exception of the 1935 value obtained by Thompson and co-workers.

DISCUSSION

The concentration of iron in the characteristic deep water of the North Pacific approximates 8 μg/L, with slightly greater than half of that value being contributed by the particulate iron (4.5 μg/L). This value, though lower than the previously accepted values, is in accord with the only other reported value which includes the deeper water of the Pacific (Table I, ref. no. 32).

Soluble iron values are far greater than those that can be accounted for by ionic iron at equilibrium with the constituents of sea water at a pH of 8. This value was shown by Cooper (1937) to be not more than 5×10^{-8} μg/L. The ferrifluoride complex ion FeF_6^{---} has been suggested by Thompson, et al. (1932) as a form of soluble iron in sea water, but Cooper (1948) has shown empirically that it is thermodynamically unstable. It is likely that the soluble iron found in this and other investigations consists of dissolved or colloidal organic compounds which arise from the marine biosphere; likely it also consists of the colloidal inorganic compounds such as ferric hydroxide and ferric phosphate. These colloidal species are of such dimensions that they pass through filters of approximately 0.5 micra porosity. Furthermore, these forms are quite uniformly dispersed throughout the oceans, evidence for which is found in the agreement between samples from deep and coastal waters and between the results of this work and that of previous investigators.

The occurrence of two populations of particulate iron in the three easternmost stations of the Trans-Pacific Expedition (Stations 7, 12, 20) and in the earlier California coastal work is probably related to the activity of the inhabitants of the marine biosphere. The accumulation of particulate iron by diatoms is followed by either the death of the organism or the uptake of the organism by higher members of the food chain. Inasmuch as many of the latter organisms are involved in the vertical migrations of zooplankton, defecation and mortality by this group together with concurrent re-uptake of the discarded matter result in the cycling of iron in the upper water layers. Thus, the marine biosphere acts as a reservoir for iron particles and accentuates the high scatter of the particulate iron distribution. Relative homogeneity of particulate iron content reflects low biological activity or high rates of mixing of waters.

SUMMARY

1. It is feasible experimentally to differentiate the iron in marine waters into two classes: "particulate iron" which is retained on a molecular filter and "soluble iron" which passes through the molecular filter.

2. In the northern Pacific the soluble iron in surface and deep waters shows values varying but slightly about 3.4 μg/L.

3. The particulate iron in waters deeper than 500 m averages 4.5 μg/L whereas in shoaler waters the values are ofttimes higher and show a larger amount of scatter. For some stations in the North Pacific the upper and lower iron concentrations, as determined from analyses of variance upon the data, are significantly different.

4. High values of iron in surface waters are attributed to the turnover of iron within the marine biosphere. As a result of the interaction between biosphere and hydrosphere with respect to iron, the upper waters act as a reservoir for iron.

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ESTABLISHMENT OF A FORAGE FISH, THE RED SHINER *(NOTROPIS LUTRENSIS)*, IN THE LOWER COLORADO RIVER SYSTEM[1]

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It has been recognized for some time by those concerned with the fish management of the lower Colorado River that some of the numerous bait minnows brought in from diverse regions (Miller, 1952) may become established, for better or for worse, in the river and connected waters. Since the native fish fauna has become largely replaced by introduced game and pan fishes, as shown by the survey of Dill (1944, p. 144-146) and, more emphatically, by recent field work, it has been thought that the establishment of an essentially nonpredatory forage fish might increase the production of game fishes. It is therefore of interest and potential importance to note the recent establishment in the lower Colorado River system of such a forage fish, namely, the red shiner, *Notropis lutrensis* (Baird and Girard) (Figure 1). The name "red shiner" refers to the color of the body and more particularly of the fins, especially in the gorgeous breeding males. Because of its abundance and small size, this shiner is an important forage fish. It has also been valued as a home aquarium fish.

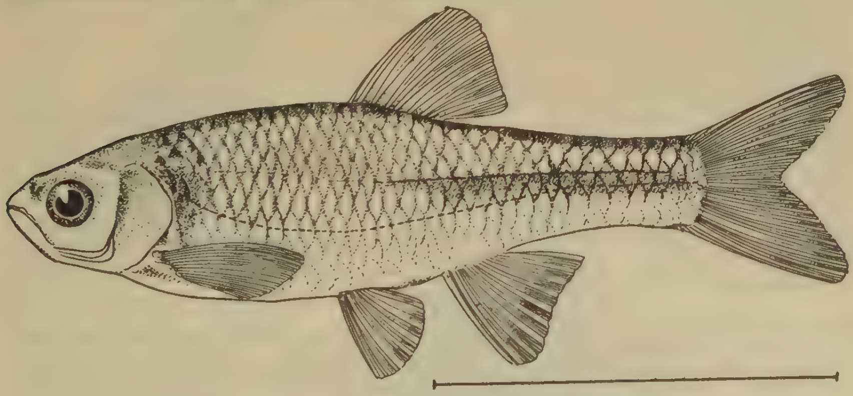

FIGURE 1. Red shiner, *Notropis lutrensis*, from Miller (1952).

THE ESTABLISHMENT

That the establishment has been recent is indicated by the lack of this species not only in the collections reported by Gilbert and Scofield (1898) and by Dill (1944), but also in more recent seining. In March, 1950, Robert Rush Miller, the author, and assistants collected in the

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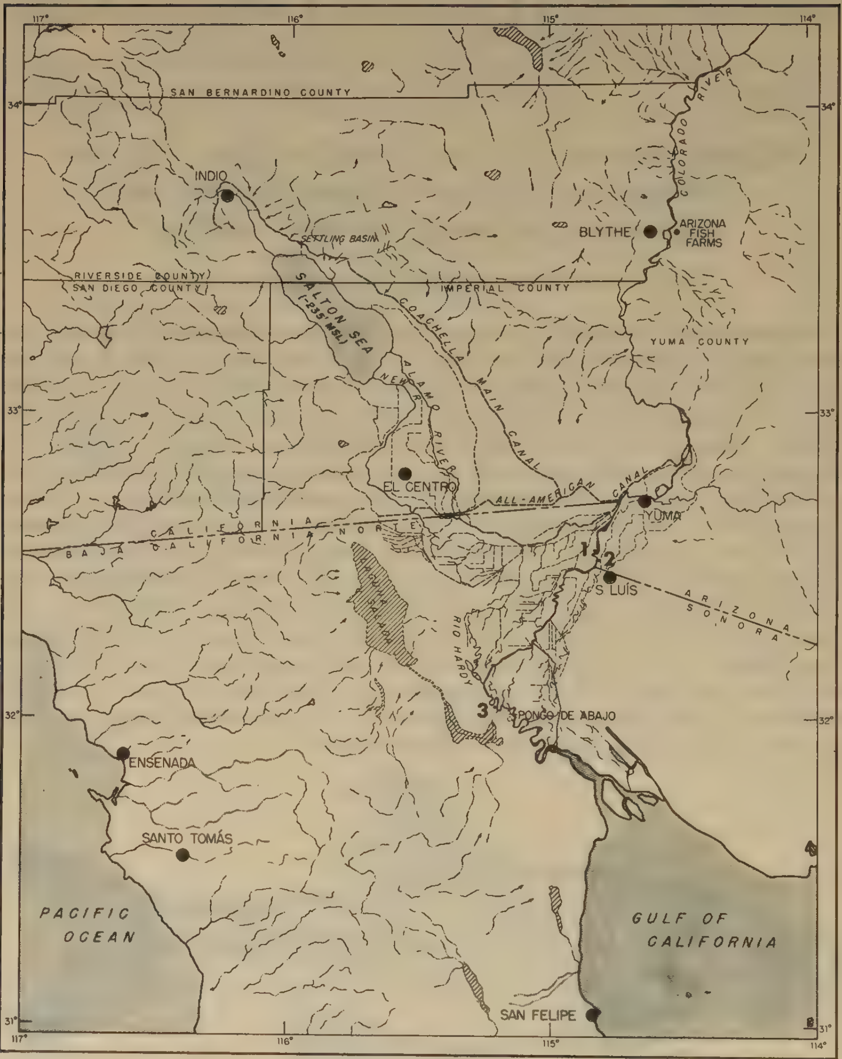
117°
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31°
SAN BERNARDINO COUNTY
COLORADO RIVER
INDIO
SETTLING BASIN
BLYTHE
ARIZONA FISH FARMS
RIVERSIDE COUNTY
SAN DIEGO COUNTY
IMPERIAL COUNTY
SALTON SEA
(-235' MSL)
COACHELLA MAIN CANAL
ALAMO RIVER
NEW RIVER
YUMA COUNTY
EL CENTRO
ALL-AMERICAN CANAL
YUMA
CALIFORNIA
BAJA CALIFORNIA NORTE
1
2
S LUIS
ARIZONA
SONORA
RIO HARDY
3
PONGO DE ABAJO
ENSENADA
SANTO TOMÁS
PACIFIC OCEAN
GULF OF CALIFORNIA
SAN FELIPE

FIGURE 2. Sketch map of the lower Colorado River system, including the Delta and Salton Sink, showing by numbers where red shiners were taken along the river in 1953. Drafted by Robert G. Kirk primarily from state base maps and topographic sheets by the U. S. Geological Survey, from World Aeronautical charts, and from maps and data furnished by the International Boundary and Water Commission (Ing. José G. Valenzuela), Imperial Irrigation District (B. A. Weiss), and Coachella Valley County Water District (C. S. Hale).

lower Colorado River over the same region where the species was taken in January, 1953, but failed to obtain a single specimen of this species.

The first collections of the red shiner in the Colorado system were made by Kenneth S. Norris, A. A. Allanson, and party, during a boat trip down the main river undertaken for the author in January, 1953 (Figure 2). The first three collections contained specimens of this species. Collection H53-1, made in the river in Baja California Norte, 2 miles south of Gadsen, Yuma County, Arizona, on January 18, contained 149 young to adult specimens 17 to 46 mm. in standard length. Collection H53-2, made in a backwater of the river in Arizona, 2 miles north of San Luís, Sonora, on the same day, included 9 half-grown to small adult specimens 20 to 31 mm. long. A single small adult 30 mm. long was seined at Station H53-3, in the river in Baja California Norte an estimated 15 miles, by the Río Hardy slough and the river, below El Mayor, on January 20. Subsequent collections farther downstream (H53-4 to 7, 9, and 10), ranging from 2 miles above the Pongo de Abajo Ferry (which is directly east of a point on the San Felipe Highway 8.5 miles south of El Mayor) to the estuary about 10 miles by river above the mouth, contained no red shiners.

The next collection of the red shiner from the Colorado River system (W53-410), kindly made available by Dr. Boyd W. Walker, was taken by John E. Fitch and Wayne J. Baldwin on December 3, 1953, in one of the pools, then becoming dry, of the settling basin of the Coachella Valley County Water District, in Riverside County, California. This settling basin is 124.5 miles from the Colorado River *via* open earth-lined canal (36 miles along the All-American Canal and 88.5 miles on the Coachella Main Canal, which continues 37.5 miles farther as a concrete-lined open ditch). Between 500 and 700 of the shiners were taken in a tied-mesh minnow seine, but only 94 young to adult specimens, 15 to 50 mm. long, were preserved (Mr. Fitch reported some selection of larger fish). On December 15, while rescuing game fish in the same basin with a coarse-mesh seine, Richard D. Beland found one dead and

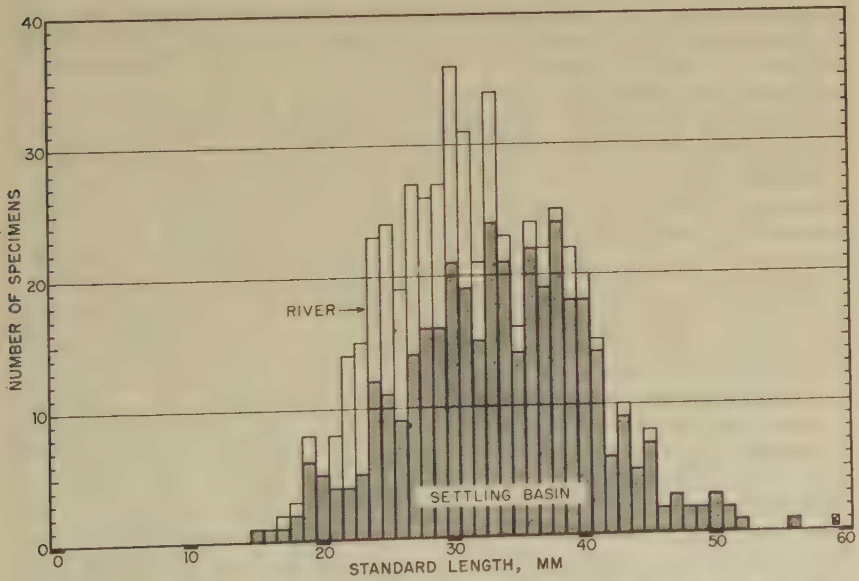

FIGURE 3. Size frequency distribution of red shiners collected in the settling basin of the Coachella Valley branch of the All-American Canal in December, 1953 (shaded columns) and in the lower Colorado River in January, 1953 (white columns).

one live specimen of the same shiner. On December 28 John E. Fitch, using a ''Common Sense'' minnow seine, obtained here a larger, unselected series, comprising 284 specimens 18 to 56 mm. long. The size frequencies, however, are approximately the same as for the December 3 collection.

That the species has rapidly become well established in the Colorado River and connected waters is indicated by the rather large number of specimens collected in 1953 in Arizona, Baja California Norte, and California, and by the widespread occurrence of young. The size-frequency distributions of the several collections (Figure 3) reveal that the red shiner in its new home breeds over a prolonged period, as it does in its native range (Hubbs and Ortenburger, 1929, p. 34; Ward, 1953, p. 20). By winter the young of the year, though in part still small, grade in size into the yearling and older groups. The rapid increase in numbers indicates that the new waters are well adapted to the species and emphasize anew the lack of faunal saturation in the western streams, particularly after the abrupt depletion of the limited native fish fauna. The Colorado River waters where the species has taken hold appear to be rather similar to the larger streams of Oklahoma and western Arkansas where it abounds, as well as in small streams of various types (Hubbs and Ortenburger, 1929). The annual fluctuation in the temperature of the Coachella Valley Branch of the All-American Canal, according to Mr. C. S. Hale, General Manager of the Coachella Valley County Water District, is from 48 to 86 degrees F. (probably the approximate range encountered by the species over much of its native territory).

There is circumstantial evidence that the lower Colorado system has become populated by red shiners through escapements from the ponds of the Arizona Fish Farms, Inc., at Ehrenburg, Arizona (near Blythe, California), though escaped or dumped bait may have contributed to the establishment of the species. The rearing of this minnow at the Arizona Fish Farms for the forage of channel catfish and for sale as bait has been reported by Miller (1952, p. 34). Richard D. Beland says (personal communication, 1953) that red shiners abound in some of the ponds, from which many have escaped into ditches on the Arizona side of the river, but that he has not taken the species in the river proper. A special effort by him to obtain specimens with rotenone in two small bays of an oxbow on the California side of the river, 2 miles north of the bridge at Blythe, on December 4, 1953, was not successful. His report (letter of December 11) adds: ''I believe *N. lutrensis* was first propagated at the Arizona Fish Farms in 1948. They have been sold for bait along the river from Needles to Imperial Dam.'' Kirby H. Walker heard in 1949 that the spawning activities were under way for the second year. J. Bruce Kimsey reports (in letter dated December 17): ''Mr. Hill of the Arizona Fish Farms near Blythe advised me large numbers of fry pass out through the screens into the river each time the brood ponds are drained, so its establishment seemed inevitable. A series of small minnows were noted by me on December 10, 1953 on a sand bar at Walker's Fish Camp, south of Blythe.'' Though these minnows were not sampled, it is highly probable that they were red shiners.

The stock of red shiners at the Arizona Fish Farms is reported to have come from the vicinity of Lake Buchanan in Texas (Miller, 1952, p. 34), on the basis of information furnished Dr. Miller and me by Kirby H. Walker, who had consulted with officials of the company. Lake Buchanan is a reservoir on the Colorado River (of the Gulf of Mexico drainage), in Llano and Burnet counties, Texas.

IDENTIFICATION

The identification of these shiners as of the species *Notropis lutrensis* (Baird and Girard) is indubitable. The characters agree fully with those of the species and in nearly all respects with those of the typical subspecies, the Plains red shiner (*N. l. lutrensis*), as these characters have been determined by me (in Hubbs and Ortenburger, 1929, p. 33-34, 73-76; and in MS) and by Clark Hubbs, who, at the University of Texas, is conducting statistical and experimental studies on this species and its close relatives and is considering the status of its subspecies. The anal rays (Table 1) are typically 9, rarely 8 or 10. The lateral line scales in 10 river specimens vary from 32 to 34 and average 33.33; in 30 specimens from the basin of the Coachella Valley Irrigation Canal, from 33 to 36, average 34.07. The slight difference in scale counts, as of anal ray counts, may be due to small-sample error or to direct environmental effects. The mouth is nearly straight and is strongly oblique, rising anteriorly about to the level of the middle of the pupil. The lips are not markedly thickened. The midventral black streak on the head of the adults is confined to the space between the mandibular rami. The general color is pale, with the pigment rather well spread over the scale pockets, with the lateral dark band weak, diffuse, and obsolescent anteriorly on the trunk and head, and with the lower sides unpigmented or lightly pigmented. The dark shoulder bar is well developed. The arrangement of the nuptial tubercles of the males is not evident on the specimens at hand, all of which were obtained in the winter. The young are pigmented like Oklahoma and Arkansas specimens described by Hubbs and Ortenburger (1929, p. 76), except that a middorsal file of melanophores is usually more or less evident, especially behind the dorsal fin, and the lateral dark band is obsolescent anteriorly.

TABLE 1

Anal Ray Counts of Red Shiners in the Lower Colorado River System

Locality	Anal rays			No.	Mean
	8	9	10		
River in Arizona and Baja California	18	130	5	153	8.91
Settling basin of Coachella Valley Canal	5	84	5	94	9.00

Identification to subspecies is complicated by the fact that the stock came from a region in Texas where *Notropis lutrensis lutrensis* appears to intergrade with a form of the southern coastal plain of Texas that may well rank as a distinct subspecies, which would probably bear the name *Notropis lutrensis suavis* (Girard). Compared with typical *N. l. lutrensis* this local form ordinarily has a slenderer body, smaller fins, and, in the ripe males, fewer tubercles. It also usually has a slightly reduced average number of anal rays, about 8.7 rather than about 9.2. The depth of the body seems to provide the best distinction. Clark Hubbs has provisionally determined that, as a rule, the distance from the dorsal origin to the anal origin in the adult males is less than .31 of the standard length in *N. l. suavis* and more than .33 in *N. l. lutrensis;* in the adult females, less than .29 in *suavis* and more than .30 in *lutrensis.* In this respect the specimens from the settling basin of the Coachella Valley Branch of the All-American Canal, taken December 28, agree rather well with *suavis:* in 38 males 37 to 56 mm. long the distance between the origins of the dorsal and anal fins measures .25 to .30 of the standard length, with an average of .278; in 31 females 37 to 51 mm. long, .25 to .29, with an average of .273. But many of the specimens were small adults, none were breeding, all were taken in the winter, and some showed a degree of parasitism and emaciation that could be attributed to crowding in desiccating waters. The number of anal rays (Table 1) is intermediate. These determinations, and more especially the circumstance that Clark Hubbs has identified material from the source region of our stock as intergrades between *suavis* and typical *lutrensis,* lead me to identify the introduced stock provisionally as intergrades (*Notropis lutrensis: lutrensis* × *suavis*).

The specimens from the settling basin are indicated as even more slender when the greatest depth is stepped into the standard length. In 113 of the largest specimens taken on December 3 and 28, divided about equally between the sexes, this measurement is 3.7 to 4.7, with an average of 4.29. For Illinois specimens Forbes and Richardson (1920, p. 144, col. pl. opp. p. 143) give: "depth 2.7 to 3.2 in adults, the young more slender."

The retention of the slender form in various habitats where the species has been established in the lower Colorado River system, in places where competition is presumably slight and food probably plentiful, provides strong evidence that the slenderness of the form called *N. l. suavis* is genetically determined, though the possibility remains that the body form may be determined, at least in part, by the environment, interacting with hormones. The depth of the body in *N. lutrensis* is subject to wide fluctuations, both individual and regional, and increases with age, especially in the males. These fluctuations are largely responsible for the abnormally long synonymy borne by the species (Hubbs and Ortenburger, 1929, p. 74-75).

The genus *Notropis* has not previously been reported from either California or Baja California Norte and the species is new for these states and for Arizona. The native range of *Notropis l. lutrensis* is from Illinois and South Dakota westward and southwestward through the Great Plains, with the southern limit in the Río Grande, Río San Fernando, and Río Soto la Marina systems of the Atlantic drainage of northeastern México. One localized subspecies, *Notropis lutrensis blairi* Hubbs (1940, p. 6-8), has been described from Texas. It may prove to be a distinct species; on the other hand, some of the nominal species now recognized from the disrupted segments of the Río Grande complex on the Sonoran Plateau of northern México may on more critical study be regarded as subspecies of *N. lutrensis*. Because of the inconsistency of its two chief features, the slender body and the large eye, I now treat as *N. lutrensis forlonensis* Meek the form inhabiting the Río Pánuco system in mideastern México that has been called *N. forlonensis*.

It is obvious that the material under discussion is not referable to *Notropis mearnsi,* which was described from the Río Yaqui system in Sonora by Snyder (1915, p. 582-584, fig.) and has since been taken in the same system in Arizona (Miller and Simon, 1943). As Snyder indicated, that form has smaller scales (about 40 in the lateral line) and usually only 8 anal rays. The same kind, or complex of similar forms, occurs in other Mexican tributaries of the Gulf of California. It should probably be called *N. formosa mearnsi* Snyder. *N. formosa formosa* (Girard) is one of the forms in the interior drainage of the Sonoran Plateau, itself perhaps only subspecifically differentiated from *N. lutrensis.*

The red shiner may be recognized, at least as an adult, by comparison of specimens with the colored plate in Forbes and Richardson or with the figure given by Miller (1952, p. 21), reproduced herewith as Figure 1. Miller's figure shows well the characters visible in side view, except for the black stippling of the interradial membranes of the dorsal fin. The slenderer body of the introduced form must be kept in mind in comparing specimens with the published figures.

SUMMARY

The red shiner, *Notropis lutrensis* (Baird and Girard), native from the North Central States to northeastern México, has recently become established in the Colorado River and connected waters of Arizona, Baja California Norte, and California, where it is of potential importance in game fish management. The recent great depletion of the limited native fish fauna accounts for the rapid increase of this and other introduced fishes in the lower Colorado River system. The establishment of the red shiner is attributed to escapements from the Arizona Fish Farms near Blythe, California. The stock came from near Lake Buchanan, Texas. The introduced fish are provisionally regarded as intergrades between *N. l. lutrensis* and *N. l. suavis,* a slender race of the southern coastal plain of Texas. They are not *N. mearnsi* Snyder, a form of the Gulf of California drainage that should probably be treated as a subspecies of *N. formosa* (Girard). That form and certain other nominal species, of the interior drainage of the Sonoran Plateau, may also prove to be interpretable as subspecies of *N. lutrensis. Notropis forlonensis* of the Río Pánuco system in eastern México is definitely so regarded.

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大洋の海底* I
(Taiyo No Kaitei)

奈須紀幸**
(Noriyuki Nasu)

神秘の壁につつまれて，大洋の海底構造については永らく人間のさまざまな臆測を育ててきた．しかしこの実用的価値から遠い領域にも，大戦後各国から競って探査の手がのばされ，過去のさまざまな推定はくつがえり，また地質時代の気象・海況，海洋上の重力測定，地球構造の熱力学的究明に関する最近の成果をとりいれては，大洋海底の地殻構造・大陸棚・海谷・海溝・海膨・海山などの成立に関する理論に著るしい進展を示してきた．

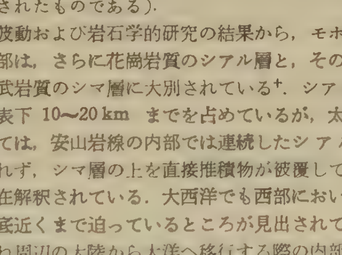
地球全表面の 70% あまりを占める広大な領域であるが，大洋の海底はその詳細に至っては今日なお未解決の問題が山積している．Challenger 号（1873～76）に始まる幾度かの海洋調査*** は，各国政府の積極的な援助を得て数々の業績をもたらし，次第に我々の知識を増加せしめつつはあるが，深海底の調査は実際的な利用価値が少く，また出費が莫大であるため，等閑に附せられてきた感はまぬがれない．ただ浅海，特に陸棚に関しては調査が容易である上に資源開発の要求も伴って深海に比し遙かに綿密な研究が行われた．

ともに生物学・地球物理学・地球化学・地質学等のあらゆる面から調査されているが，小論では海底地質学の立場のみに限定して，大洋底の地形・底質・成因論を概観する．

大陸と大洋底

かつて一度も，真の意味での大洋底からその基盤の岩石が採集されたことはなかった．堆積物がその面を被覆しているからである．僅かに大洋中の島々の岩石学的研究に基いて，基盤の様相が想像されていたにすぎない．重力分布と地震波の伝播速度とが研究され始めてからは，その内部構造が余程明確に解釈され得るようになったといえよう．これによると，大陸と大洋底とでは，単に海水に覆われているか否かの差異のみでなく，その地下構造をも異にしている．自然発生地震および人工地震による観測結果では地球内部に進むに従って幾枚かの層があり，地震波の伝播速度は（二三の例外を除いては）内部の層ほど速くなる．各層の境では地震波動の反射も見られる．この現象は特に Mohorovičić 不連続面（以後は単にモホ層と呼ぶ）において著しい．一般にこの層は，地形が高いところでは深く，低いところではより浅く位置している．大陸や大洋底の安定した部分では，この層においてアイソスタシーが成立していると考えられている．すなわち平均して密度のより低い固化した地殻が，密度のより高い超塩基性基底層（dunite）の上に浮かんでおり，両者の不連続面がモホ層に相当するものと考えられている．その深度は大陸の低地域で 30 km 前後，高山帯の下では 50 km 前後に達する(1)．海洋底においてはこの深度は浅い．なかでも太平洋のほうが大西・インド両洋に比較してより浅いところに位置するであろうと GUTENBERG（1951）(2)は示唆している．OFFICER, EWING（1952）(3)によると 10km の厚さの点が大西洋中にあり，太平洋では 5～9 km が典型的な値として報告されたのである(2)(4)（1940 年代にはこの深度が大陸のそれよりもさらに深いと考えられていたのだが実測の結果改訂されたものである）．

地震波動および岩石学的研究の結果から，モホ層上の地殻内部は，さらに花崗岩質のシアル層と，その下位にある玄武岩質のシマ層に大別されている+．シアル層は普通地表下 10～20 km までを占めているが，太平洋底においては，安山岩線の内部では連続したシアル層は認められず，シマ層の上を直接堆積物が被覆しているものと現在解釈されている．大西洋でも西部においてシマ層が海底近くまで迫っているところが見出されている．おおむね周辺の大陸から大洋へ移行する際の内部構造の変化は太平洋において著しく，大西洋では漸移している



第1図 大陸と大洋の対蹠関係（UMBGROVE(6)）

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* Contribution from the Scripps Institution of Oceanography, New Series No. 716

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*** 第二次大戦後はデンマークの Galathea（1950～1952），スウェーデンの Albatross（1947～1948），イギリスの Challenger（1950～1952）が世界一周の深海調査を行った．アメリカの Scripps 海洋学研究所は Horizon, Crest, Spencer F. Baird の 3 隻を駆使して 1950 年以来 Mid-Pacific（1950），Northern Holiday（1951），Shellback（1952），Capricorn（1952～1953），Trans-Pacific（1953）と既に 5 回に亘って太平洋各海域へ Expedition を行った．昨年度訪日した Baird 号の太平洋横断はこの 5 回目に当る．大西洋側では Woods Hole 海洋学研究所ならびに Lamont Geological Observatory の調査船が現在活躍している．

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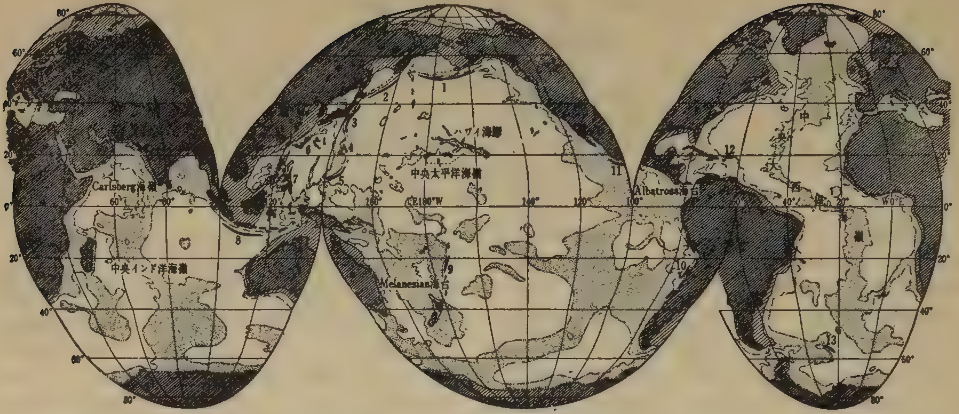

第２図　海底地形略図（SHEPARD(7)）

1. Aleutian 海溝，2. 千島海溝，3. 日本海溝，4. 小笠原海溝，5. Mariana 海溝，6. 琉球海溝，7. Philippine 海溝，8. 東インド海溝系(Sunda 海溝)，9. Tonga-Kermadec 海溝，10. Andean 海溝．11. Acapulco 海溝，12. Puerto Rico-Antillean 海溝，13. South Antillean 海溝．

点が強調され，インド洋も大西洋に類似であると称されてはいるが(2)，大西・インド両洋の主部が太平洋の主部とその内部構造を異にしているのか否かは今後に残された問題である*．かつては太平洋底にはシアル層が欠除し，大西・インド両洋底には存在するものと簡単に考えられ，海洋底の成因を論じた諸説も，この仮定の上に立って，より古い説を否定し新説を唱えた（UMBGROVE(6)等）．しかしこの事柄が再検討を迫られている今日，大洋底の成因論も同様再検討の時期に際しているものといえよう．

重力異常に関しては，アイソスタシーの考え方から当然，より密度の低い地殼がより深くまで位置している大陸側では負に向う傾向が強く，より密度の高い地殼および基底層が地下浅所まで迫っている大洋底の安定部では正に偏る傾向が生じることは容易に理解できる．

つぎに大陸と大洋の水平分布に目を転じるならば，四つの重要な事実を列挙できる．すなわち (1) 各大陸はほぼ四面体の四頂点に位置する恰好になり，これを地球の中心を経て正反対の側へ投影するとほとんど大洋の中に落ちる．他の大陸上に投影されるのは5％にすぎない（第１図）．(2) 各大陸はほぼ三角形を成し，最鋭角は南を指示している．(3) 幾つかの大陸の周辺の線は見掛け上平行である．(4) 各大陸は二つずつ対を成してほぼ同子午線上にならび，その北は北極海を繞って集中し，陸半球と海半球の別を自ずと形成する(6)．

以上の地理的分布の特徴および大陸と大洋底の内部構造の相違は，その起源を考察する際にしばしば引用される．その点については最後の章に述べよう．

海底地形

古い昔から船舶の安全を守るために海岸附近の測深は無数に行われた．しかし深海測深は 1839 年に ROSS 卿が索を用いてはじめて成功を収めて以来，音響測深に代わるまで僅かに 15000 点程度の値が得られたにすぎなかった．例えば MURRAY が 1855 年に始めて北大西洋の海図を出した時，それは 200 点に満たない測深値に基づいて作製された程度のものであった．かつての海底地形図が，堆積による平坦化という先入観と相俟って，実際よりは遙かに単調に画かれざるを得なかったことは容易に

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† GUTENBERG(2)は高温になるに従い，α-石英のヤング弾性率が漸減し，遂に β-石英に変じてふたたび一定の値に戻る事実を指摘して，シアル層の中に伝播速度の遅い層が存在する可能性を唱え，かつこれが浅発性の震源となりやすいことを併せ説明している．この層が波動の屈折を齎して，ある方向に進む波はこれがために地表に達することができない．この層の上部での最大伝播速度は 6.5～6.75 km/秒であるから，反射波の中で地表に到達し得るものは，この層の下で一旦この最大速度と同じ伝播速度を有する層まで達してから反射屈折したものでなくてはならない．これがしばしば 7 km/秒の層の存在と誤って解釈された原因であるとしている．またこの層が花崗岩層の内部に位するものか，下位に位するかはいまだ不明であり，また海洋底にこの層が欠除することを証明するにもデータが少なすぎることを述べている(1)（モホ層の下位の基底層内の P 波は 8～8.5 km/秒が通常）．

* GASKELL(1954)(5)は Challenger 号による観測結果に基いて，差異なしとの意見に傾いている．

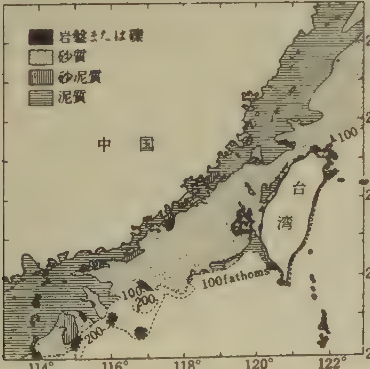
了解できる．しかし最近の連続音響測深法の使用・発達により海底起伏の状態は急速に明らかにされつつある．その輪廓は両極附近を除けば，今日までにほぼ判明したものといえよう．第２図にこれを示す．

海底地形は深度により，陸棚・陸棚斜面・海溝・深海底に大別できる．平面的には周知のごとく，太平・大西・インド洋に大別され，これに南氷洋・北極洋を加えることができる．

陸　　棚

大陸や島弧の周辺に見られる浅海が陸棚であり，しばしば広大な面積を占める．全海洋下の 7.6% は陸棚であるが地下構造からいえば大陸性である．潮線を越えて陸棚端まで続くゆるやかな傾斜（平均，0°07′）であり，その先は折れて深海底へ下向する（上部の平均傾斜 4°17′ 程度）．この部分を陸棚斜面と呼ぶ．陸棚端の水深はところにより差があるが，各大陸を通じて平均 100～200 m 前後と称され，これは陸棚の成因を論じる際にしばしば引用される．氷蝕を蒙った地方では陸棚端はより深い所に位置している．各大陸とも広大な陸棚を伴う中で，アフリカ東海岸および南アメリカ西海岸は例外であり，ほとんどこれを欠いている．北アメリカもその南部は陸棚の代りに凹凸の顕著なボーダーランドを抱えている点が他と異っている．陸棚斜面や陸棚を截る海谷の存在は近時論争の一焦点となった観があるが，これについては次項に述べる．

SHEPARD (1948)(7) は地形および底質の点から陸棚の特徴をば次のように述べている．(1) 陸棚の幅と陸棚端の水深とは無関係．(2) 陸棚表面は段丘そのほかの起伏を伴う．(3) 堆積物の平均粒径が岸から距るに従って細粒化するといった普遍現象は認められない(8)（第３図）．(4) 基盤の露出や礫の分布は陸棚の外半に多い．(5) 現在実際に河川等により供給されているものより粗粒の堆積物によって被覆されている（これは第四紀の氷期における海面低下が齎した堆積状態がいまだに保存されていることを SHEPARD が暗示しているものと解釈される）．(6) 氷蝕棚は他の陸棚と趣きを異にし起伏が激しい．(7) 大河のデルタは陸棚端を越えて成長しつつあるものも存在はするが（Mississippi 河口），通常は陸棚内に位置する．(8) 海緑石（glauconite）や燐灰土（phosphorite）の存在がしばしば報告されるが，これは，陸棚上においてそれらを産する堆積の休止状態を示すものと考えられる（南 California 沖や南アフリカ沖）．(9) 砂質は外洋に面した起伏の少い陸棚上，長距離連続する砂浜の沖，狭小な湾口の沖，氷蝕陸棚のバンクの上などに多く分布する．(10) 泥質は大河の河口附近・湾内・陸棚上の凹部に分布する．(11) 礫や岩盤は湾口・岩石の多い岬の沖・波浪侵蝕を蒙った海崖の附近，急潮の存在する外洋の陸棚・または陸棚上でも凸部に多く分布する．(12) 陸棚斜面では概略してその面積の 60% を泥質が，25% を砂質が，10% を岩盤や礫が，残る 5% を介殻や軟泥が占める．



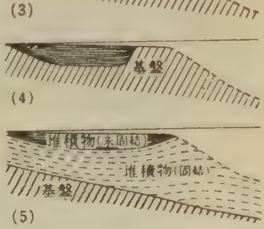
第３図　東および南支那海の堆積物分布(7)

Vening MEINESZ (1941)(9) は潜水艦を使用して，海岸から陸棚を越え深海の上へと世界各地で 26 の線を選び，その重力分布を調査した．その結果，陸棚から陸棚斜面にかけては重力異常が負であり，海洋の上に移る際にその値が増加する事実を認めた．そしてこれは大陸の上層を占めるシアルの層が海洋底に移る際に薄失するためであると解釈している．

始めに BULLARD(10) 等，後には HILL(11) 等が英仏海峡で，また EWING(12) 等がアメリカ北東海岸で行った地震探査の結果からは，調査された陸棚の下に相当程度の厚さの堆積物が存在していることが示唆されている．

陸棚および陸棚斜面の成因に関する諸説を要約すると，陸棚表面の平坦化が波浪の営力によるものである，という点では意見の一致をみている．また第四紀の氷期においては海面が現在位置より 50～150 m ほど(13) 低下していたであろうとの説を受け入れて，陸棚端の水深が 100～200 m 前後に平均しているのは当時の波浪侵蝕や波浪の営力が与って力あったものとしている．なぜなら現海面上においての波浪の影響を蒙る水深は遙かに浅いと考えられているからである．

表面の平坦化については，(1) 陸棚の内半



第４図　陸棚の成因に関する諸説(7)

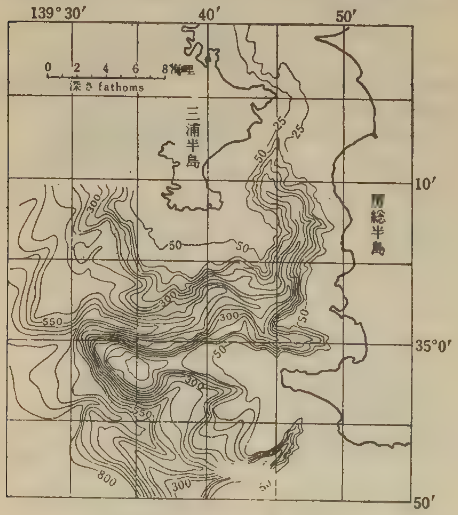
は波浪侵蝕により，外半は波浪の堆積作用によった.(2) 沈降過程にある基盤の上に堆積が行われ，その表面は波浪によって平坦化された(以上デルタ型式). (3) 全く波浪侵蝕のみによる. (4) 大陸を繞る島弧が波浪侵蝕によって海面下に没し，本土との間の深所は堆積物により埋没した. (5) 地質時代の長期に渉って堆積が連続し，厚層の堆積物を陸棚下に蓄えている，などの諸説がある(第4図).

陸棚斜面の形成については，(1) デルタ前縁傾斜に相当する. (2) 断層による. (3) 地殻表面の撓曲による，などの説が唱えられている.

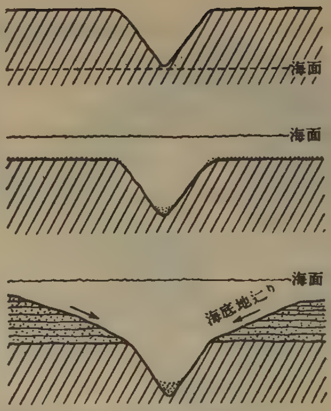
しかし筆者は，場所によりその成因を異にする可能性が考慮されてしかるべきであると考える. 将来. 資料の集積が上記の成因説のいずれが，どこの地方に該当するかを明白にさせるであろう.

海　　谷

陸棚斜面や陸棚を截って，しばしば海谷の存在がみられる. これもまた全世界に渉る広汎な現象であるが，組織的な研究が SHEPARD その他によって始められたのは 1930 年代にすぎない. しかしその成因論は近時の海底地質学上の一焦点を形成している. 日本列島周辺の海谷については，矢部(14)，新野(15)，田山(16)等の諸氏による研究があり，東京海谷（第5図）や富山海谷は外国の文献にもよく引用される. 北アメリカの New England 沖には Oceanographer, Hudson, Wilmington 等多数の海谷が存在し，California 沖では Monterey, Carmel, Redondo, La Jolla, Coronados 等の海谷について詳細な調査が行われつつある. ヨーロッパ大陸周辺や地中海その他にも多数の海谷の存在が報告されている. SHEPARD(7)によれば海谷の特徴は，(1) 陸上の谷とその形態が類似し，底は始め強く，後に緩やかな傾斜を保ちつつ下向する. (2) V 字形断面を有する. (3) 蛇行する. (4) 支流を持つ. (5) 両側の斜面からしばしば基盤の露出が報告されているが大部分は堆積物によって被覆されている. (6) 谷頭が陸岸近くまで迫っている場合，岸に沿って移動する砂質でその谷頭が埋没していることがある. (7) 大規模な海谷は，谷頭の方向への延長が陸上の谷へと接続する場合が多い. (8) 海谷の深海への終端はデルタ形または扇状形を示すか，あるいは構造的影響に従う. 小数のものは平坦面で終る. 終端の水深は個々の海谷によって異るが，普通 1000 m から 3000m の間に位置する.

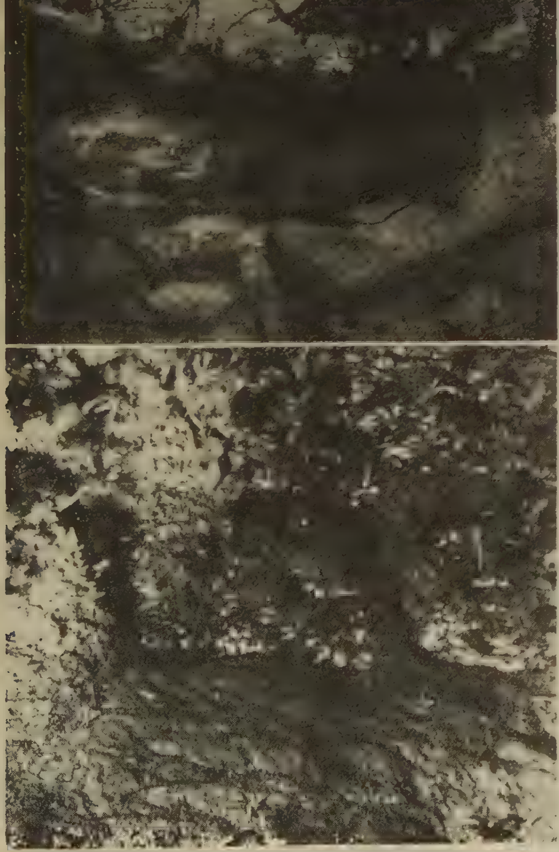


第5図　東京海谷(7)



第6図　SHEPARD(7)による海谷の成因

海谷の成因論は，相対的な海面低下に伴って現在の陸棚や陸棚斜面の位置が陸上に一旦露出し，侵蝕を受けて陸上谷を形成してこれが後ふたたび海没して海谷となったとする陸上侵蝕説，海面下の地辷りや乱泥流（turbidity current）等によって形成されたとする海面下侵蝕説，および以上の折衷説の三者に大別される. SHEPARD は始め第一の説(7)を採り，後に第三の説(17)に改め，KUENEN は始め第二の説(13)を採り，最近に第三の説(18)に代った. ここには両者の考え方を紹介ずるに止める. SHEPARD(第6図）は地質時代のある時期に海面は現在より相対的に非常に低下していたこと(複数)があり，その際現在の陸棚斜面や陸棚の位置は海面上に露出した. これが侵蝕を受けて陸上谷が刻まれ，その終端にはデルタが形成された. のち海面上昇に伴ない谷は海没し，大陸周辺には堆積物が累積した. しかしすでに存在していたこれらの谷に沿っては時折地辷りや乱泥流が起り，絶えず原形を保持しようとする営力が働いたものと考えられる. 下って第四紀の氷期における小規模の海面低下（100 m±）は谷頭附近の侵蝕を増大し，支流をもまた拡大したであろう，とのべている. 海面下 1500 m 前後の

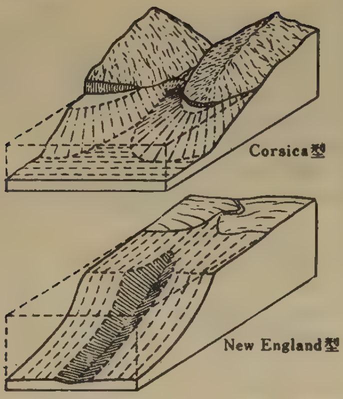


海谷の様相　上：Scripps 海谷・Sumner 支流の北壁と急下向する谷底（深度 30 m, SHEPARD 博士提供），中：Scripps 海谷の谷頭附近（深度 15m），下：同海谷北西壁と底面（堆積物被覆）との接触部（深さ約 100m, R. McALLISTER, H. STEWART 両氏の撮影による）.

水深に頂を持つ海山の表面から採集された化石が後期白堊紀の浅海性を指示する点(後述)，珊瑚礁・陸棚のボーリング結果などを考慮に入れて，白堊紀から古第三紀の間に全世界に渉る大規模の海面低下（1000mを越える）が始めの陸棚侵蝕を齎したものと考察している.

KUENENも第四紀の小規模な海面低下が100m以浅の部分の陸上侵蝕を齎し，これがその後の海面上昇で溺谷となった，とする点ではSHERARD と意見が一致しているが，それより以深の部分については見解を異にし，地域によりその成因に相違があるとしている．Corsica 島西岸に多数みられる海谷は，陸上侵蝕のみによって形成された谷が後に海没した典型的な溺谷で，海面下の侵蝕はほとんど蒙らず，その終端は 1000m を越えることなく，地中海の底までなお 1500m を残している．しかし New England 型はほとんど海面下の侵蝕によって形成されたものとしている（第７図)．すなわちDALY(19)は氷期の海面低下が陸棚表面を露出せしめ，泥質を多く懸濁せしめて陸棚斜面に沿い下向する泥流を増加し，これが侵蝕を行って海谷を刻んだものであろうとしているが，KUENENはこの説をNew England 沿岸の海谷の成因として採用している．そして自らが実験(13)(20)によってその可能性を確めた乱泥流，および海底地辷りが谷を刻み，それは現在証明できないけれども，固結した基盤の岩石に対してさえも侵蝕の偉力を奮ったであろうとしている．理由として，(1) 懸谷が見られぬ，(2) 谷底に沿い砂質や礫が存在し，その中の化石は寒冷な気候を指示しているので侵蝕は氷期の間に主として行われ，その後はあまり進まなかった，(3) 谷底に沿っては滝の存在を暗示するような階段が見当らない，(4) 谷は陸棚斜面の最大傾斜に沿う，(5) 終端は 2000m から 4500m の水深にまで及ぶ，など多数の事例を挙げている．一方世界各地に点存する海谷はNew England型とCorsica 型およびその中間型であるとの見解をとり，東京海谷も中間型の一例として挙げている．California 沿岸の海谷は，SHEPARDの説に従うものと海面下の営力のみによって形成されたものとがあり，またかつて存在した海谷でもいまは完全に陸棚の下に埋没しているものもあろうと述べている.

海面自体の昇降が世界的な規模において行われたことは明白であるが，地殻変動は極めて限られた地域内の運動から，相当広般で大規模な運動まで種々行われたであろうから，相対的な



第７図　KUENEN(18)による海谷の成因

海面の昇降が空間的にも時間的にも対象とする地域により異るのは当然である(21)(22)．この意味において，地域別に海谷の成因を見極めようとする KUENEN の最近の態度は将来も保持されて然るべきであると考える．

さていま少しく観点を変えて SHEPARD の説を検討すれば，これは暗に大陸と大洋底との境界が，第四紀はもとより第三紀を通じてほとんど現在位置附近に停滞していたことを前提としている．KUENEN もまた，北アメリカ西岸に関する限り，上述の論文中では SHEPARD と見解を同じくし，他の地域に関しても実は後述するように同様の見解を採っている．これは地質時代を通じて大陸が次第に成長したものであるのか否かという大陸と大洋底の生成過程に関しての根本的な問題と関連しており，海谷の成因論が注目を浴びつつある所以も，この辺りに一つの原因を含んでいるものといえよう．

海　　溝

大陸と大洋底の接続部にはしばしば狭長な弧を画く海溝が存在する．特に太平洋において顕著であり，北から西周りに，Aleutian (7680 m)，千島 (8500 m)，日本 (9600 m)，小笠原 (9426 m)，Mariana(10863 m)，琉球 (7480 m)，Philippine (10540 m)，Tonga-Kermadec (10600 m＋)，Andean（南アメリカ西岸）(7635 m)，Acapulco（中部アメリカ西岸）(6000m＋) 海溝が分布する．括弧内は最深測深値を示す(23)(24)(25)(26)*．インド洋ではその東縁に近く東インド海溝系 (7455m)，大西洋ではカリビア海に近く Puerto Rico-Antillean 海溝 (9199 m)(28)，南氷洋には South Antillean 海溝 (8264m) をみる（第２図）．

これら海溝の特徴は，(1) 通常大洋に向って凸，大陸に向っては凹の弧を画く，(2) 大陸側に火山性の山脈あるいは花綵列島が常に附随している．(3) 列島は一重弧と二重弧の場合がある．(4) 大洋側には著しい高まりは認められない．(5) 海溝内の重力異常は著しく負であり，海溝の両側では正の値をとる(29)，(6) 大洋を繞る地震帯は海溝と平行する．その震源はほぼ海溝内に始り大陸側へ傾斜する 30° から 55° の面に沿って浅発性から深発性へと分布している(6)(30)．後者は地殻から 700km の深さにまで及ぶことがある．(7) 磁気異常についても観測が行われているが，いまだ資料が少いために，重力異常のそれに見るような見事な結果を得るまでには至っていない．(8) 海溝はほとんど例外なく大陸側に急傾斜 (10° 前後) を持ち大洋側に緩やか (5° 前後) である．故に横断面は非対称なV字形かあるいは，\/形を示す．時により後者の中央に小規模ではあるがさらにV字形を深く刻むことがある（Tonga 海溝，日本海溝 Ramapo 海淵）．平底は堆積の結果と考察されている．(9) 海溝内の両斜面は単純な傾斜ではなく起伏を繰返しつつ漸次下向している．筆者は昨年秋 Baird 号で千島海溝から日本海溝へかけて７度横断する機会を得，音響測深儀を見守ったが，そのいずれの場合にも以上の現象が観察された．(10) 海溝は周囲の大洋底に比較して一段と深く，海洋の最深部は総べて海溝内にある．これを探知することは Everest 征服にも比せらるべき事柄であるかもしれないが，それよりも興味を呼ぶものは，これら最深部の値が相異る海溝において 10,000 m 前後で一致している点である．これは地殻強度の限界と関連しているのであろう．(11) 海溝内の堆積物 (1.5〜3 km/秒) の厚さは，人工地震探査によると Puerto Rico 海溝で約 6〜12 km (31)，Tonga 海溝 0.5km(推量)，Acapulco 海溝の東北端で 1.5km 程度で各海溝によりその値を異にする．(12) モホ層は Tonga 海溝の下では少くとも 15 km，恐らく 20 km の深さに達している(4)．これは大陸の下よりは浅く，大洋底の平均値よりは深い．(13) 海溝内堆積物についての研究は，将来資料の獲得を待つ状態にあるが，肉眼観察によると Acapulco 海溝では緑泥が見られ，Puerto Rico 海溝では遠洋性の赤粘土と浅海性の生物の遺骸を含む石灰質砂層の互層がみられた(31)．

海溝の成因については，もとよりその特殊な形態と注目を引く分布によって従来華かな論争の場を提供してきた．造山運動や地向斜形成の問題とも併せ検討されなければならない点が特に地質学専攻者の注目を浴びつつある所以でもある．その詳細をここに一々述べる余裕もないから，只一例として BIJLAARD (1936)(32) に始まり，UMBGROVE(6) によってまとめられた成因説を紹介するに止める．これは Vening MEINESZ 等(29)が行った重力

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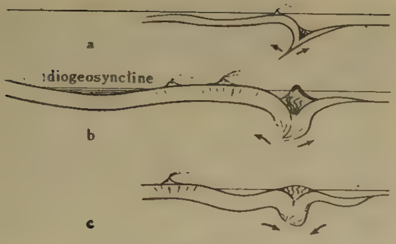
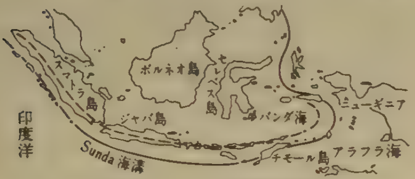
* 日本海溝ではかつてアメリカ軍艦 Ramapo によって 10550 m と発表され，Ramapo 海淵と命名されたが，昨年 Baird 号が同位置で測深した結果 9610m が得られた．また Tonga-Kermadec 海溝では 10600 m が最も新しい結果として得られた(27)．ともに公式には未発表であるが，補正計算を行った FISHER の好意を得てここに掲げた．



第８図　海溝の種々相

UMBGROVE(6)によりまとめた．矢はシマの厚さが増す方向



第９図　東インド海溝系(6)

実線は負の重力異常を伴う外弧，破線は火山性の内島弧

異常の測定結果と，GUTENBERG 等(30)の震源分布の調査結果および各島弧の地質学的資料に基ずくものである．

概略を記すと――地球内部に生起する熱対流は週期的循環を行い，地殻内部に圧力が増加する部分を作る．この過程では 200～400 km の波長の地殻の波が脈動し，その振幅が増大して遂に地殻の弱所においての強度限界を越えると撓屈（buckle）を起し，シアルの根は下層のシマの中へ深く垂下する*．ゆえに撓屈帯の上での重力異常は負の値を示す．撓屈帯の両側では地殻がやや持ち上げられているため，正の重力異常を示すのが常である．

シアルの層が薄く，大陸より遠距離の深海でこの撓屈が起れば，その上には負の重力異常を伴う海溝が形成される．Mariana 海溝，小笠原海溝はその好例である．垂下したシアルの根は下層のシマを両側へ排斥するが，大洋側へは弧が凸であるため，シマは比較的自由に拡散される．これに反し，弧の内側ではシマが累積し，圧力は増大（垂直方向にも）し，背斜軸を形成するにいたる．これはまた火成活動を伴い，海溝の内側に，これに平行に走る火山弧を形成する（第８図 a）．

シアルが大陸性の厚層の場所では，撓屈に先立ってその両側は水面上に現われ，下向する撓みの中へ陸源物質を豊かに供給するであろう．故に撓屈が行われた際にはこの堆積物は排出されて負の重力異常を示す山嶺を形成するに至る．これが海面上へ現われるか否かは始めの堆積物の量，および以後，撓屈帯の両側から加わる横圧の増減に支配される．これを外弧とすれば，その内側に火山性の内弧を形成する点は先に述べたと同様である．外弧，内弧ともどもに海面上へ現出した島々を形成すれば，これは二重島弧となる．東インド海溝内に位置するチモール島を始めとする島列は外島弧の一例であり，ジャバ，スマトラ等は火山活動を伴う内島弧に相当する（第８図 b，第９図）．UMBGROVE は琉球弧も二重島弧の一例として挙げている(25)．地殻内部の横方向の圧力増加に伴って撓屈帯の下でシアルの根がより深く垂下すると内弧の火成活動は旺盛になり，その高さをも増す．その際火山弧のさらに内側には大陸との間に凹所が生じ，これが特殊な地向斜堆積の場を提供することとなる（idiogeosyncline）．圧力が減少すればアイソスタシー調整のため，撓屈帯は浮上し，外島弧はその高さを増し，内島弧は逆にその火成活動を減じ高さもまた低下する．撓屈部の浮上に伴い，シマがこれを埋めるべく移動するので，その両側には凹所が形成される．外側の凹所は一見海溝的な形態を示すが，これは強い負の重力異常を伴う海溝とはその本質を異にするものである（第８図 c）．

このような地殻の脈動は地質時代を通じ，同じ地域で週期的に繰返されたことであろう．

Aleutian 弧も大部は一重の火山列島であるが，その東部では　重弧を形成している．日本および Philippine は数多くの弧形が互に交錯した特殊な位置を占めているので，その生成過程は複雑であり，さらに詳細な地質学上の資料の集積がその解明を齎すであろう**．アルプス・ヒマラヤ等の造山帯，ビルマの構造帯，東インドの島弧等の差異は，造山過程ではなく，むしろ造山運動が行われた位置においての地殻の厚さの差に基ずくものであろう．

そしてこれら撓屈帯は主として，大陸と大洋底の境に沿う内部構造の不連続線に沿って分布し，このような場所ではまた，横圧のため大洋側から大陸側の下へ傾斜する逆断層型の剪断面と重っている．この面の上部は海溝内へ露出する．地殻およびその下層の弱所であるこの剪断面に沿って震源の分布がみられる．

Mariana・小笠原海溝は真の太平洋底と，比較的薄いシアル層に覆われていると考えられる Philippine 海との間に横たわる内部構造の不連続線に沿うものであり，琉球海溝や Philippine 海溝は，後者と厚いシアルの層を持つ大陸との間に位置するものである．Aleutian，千島，日本海溝北部は太平洋底と大陸とが直接境を接するところに生起されたものである．

以上が UMBGROVE の説明の梗概である．将来新らたな資料の集積によって改められるべき点も多々あろうが，これを特に紹介した所以は，現在の段階として一応合理的な説明であると考えたからである．（未完）

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* ここに UMBGROVE の唱えるシマとは，地殻内部のシマのみでなく，その下位にある超塩基性物質（dunite）も含めているものと了解すれば以後の論旨も明白になる．

** この点については，古くは NAUMANN より，新しくは小林(33)，大塚(21)，江原(34)等，日本の地学者によって解釈が試みられている(35)．なお最近，坪井氏(36)等により，日本全土の重力分布がまとめられているが，この問題の解釈に重要な手掛りを与えよう．

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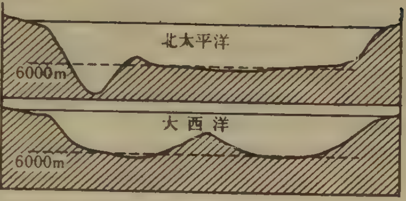
大洋の海底 II

奈須紀幸

深海底

ここでは陸棚斜面や海溝を越えて，大洋の下に横たわる広大な深海底について述べる．筆者の乏しい体験からも，北西太平洋で数十 km の間ほとんど平坦で変化なく，その精度の粗さにもかかわらず従来の海図の修正を要しないような海域があるかと思うと，一方，陸上の山岳地帯に見るような凸凹の激しい深海の地形が音響測深儀の上に画き出されていく場所もあり，これをまとめて一概に論じることの困難であるのを実感した．しかし従来得られた資料からでは大西，インド両洋の平均深度はおよそ 4000m 程度であり，太平洋は 4300m くらいである(13)．しかし太平洋周辺の海溝の存在と，中央大西洋海嶺の存在とを除外すれば，いわゆる深海底大部の深度が両者ともおよそ一致する点は注目に値する（第 10 図）．深海底の起伏が与える地形の変化により，その呼称にも差が生じる(37)．深海底のくぼみを海盆，広長で緩かな高まりを海膨，これより急斜面を持ち不規則な地形を示す細長な高まりを海嶺，非常に広大で緩かな起伏を示す深海底よりの高まりを海台という．深海底から 1000 m 以上独立して聳える海中の山を海山，その中で平坦頂を有するものにギョー（guyot）の名を用いる（ただし頂の水深が 200m 以深の場合）．高まりが 1000m 以下の場合には海丘の名が適当であろう．深海底の凹所で，その深度が 5400m を越える際には海淵の名を冠することがある．

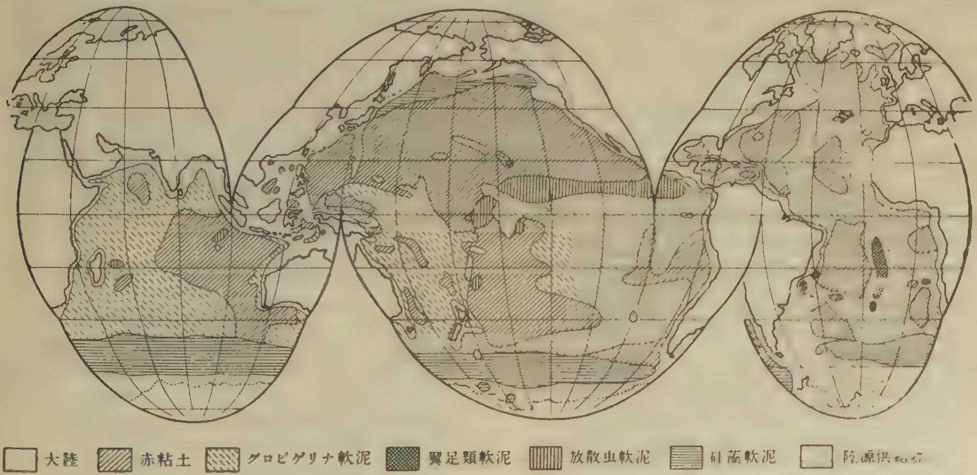


第 10 図　大洋の断面（Kuenen(13)）

太平洋では Hawaii から北西には Hawaii 海膨が走り，この上に Midway が位置する．同じく Hawaii から南西々に向っては中央太平洋海嶺が走り，これは多数の海山を包含するので注目される．また，北アメリカ西海岸から西へ向って数本の構造線がほぼ平行に延びている．これらを通じて見られる太平洋底の特徴は，褶曲構造が比較的少く，断層や裂罅性の構造線が多いことである．南アメリカ西岸から西へ広大な面積を占める Albatross 海台と，オーストラリア大陸・Tonga 海溝間に拡がる Melanesia 海台とは，岩石学的，地球物理学的見地から準大陸の名が適当であろう(4)．安山岩線は，かつて，疑点を残しつつ南アメリカ西岸に沿って画かれていたが，今後は Albatross 海台の西に引かれる可能性が強くなってきた(38)．

大西洋では中央大西洋海嶺が南北に貫いているが，赤道附近で強く屈折してほとんど東西に走る．そのため，海嶺は南北アメリカの東海岸，アフリカ，ヨーロッパの西岸とほぼ 3 本の平行曲線を画き，その両側に幾つかの海盆を抱く形になっている．大西洋中での地震活動は主としてこの海嶺の下に集中する．

インド洋では Carlsberg 海嶺に接続して中央インド洋海嶺がほぼ南北に走り，その両側にこれまた幾つかの



第 11 図　遠洋堆積物分布図　（The Ocean(24)より）

海盆の分布がある（第2図）.

深海堆積物は1855年に始めて採集された. 以来 Challenger（イギリス）, Albatross（アメリカ）, その他数多くの深海調査船によって研究が継続され, とくに第2次大戦後は **KULLENBERG** コア(39)に始まるピストン型式のコアが使用されるようになり, 20 m 程度の深さまで堆積物を比較的乱さずに採集することが可能となった（第11図）. 日本近海底質分布図(40)は本邦周辺の深海堆積物分布の様相を知る手引ともなろう.

深海の堆積物を構成する主要成分は, (1) 粘土鉱物, 水酸化鉄, 石英, その他の陸源鉱物の微細な破片が流水や風によって海水中に齎らされた後, なお長時間を懸濁して拡散されていったもの, (2) 海面近くプランクトンとして生活していた生物の遺骸が沈積したもの（これは石灰質または石英質で, 有孔虫, 放散虫, 珪藻類, 石灰質海藻, 翼足類が主要部分), (3) 陸上・海中火山から齎らされた火山灰, (4) コロイドの表面反応のような電気化学的反応で海水中から沈澱した無機物質, に区分できる(4)(41).

陸源物質が豊かに供給される深海底の表面は色彩により, 赤泥, 緑泥, 青泥, 火山泥, 珊瑚砂および珊瑚泥に区別される. 赤泥は二酸化鉄の含有量多く, 緑泥は一酸化鉄, 有機物, グロコナイトの含有量が多い. 青泥は一酸化鉄, あるいは水酸化鉄および有機質の含有によって特徴づけられている(7)(42).

陸源供給物の影響を蒙ることの少い遠洋には, 赤粘土, 放散虫軟泥, 珪藻軟泥, グロビゲリナ軟泥, 翼足類軟泥が主として分布する. 赤粘土は平均直径 1μ 程度, 実際は赤色ではなく, チョコレート色から暗赤色の間の色彩を呈する. その起源についてはまだ定説がなく, 陸源の粘土がコロイド状態で遠く運ばれたもの, 火山灰の分解したもの, 宇宙塵より, など考察されているが, 目下のところ, 陸源説が優勢である. 赤粘土は広く遠洋底のほぼ30%を占める. グロビゲリナ軟泥はさらに広く分布し50%を越える. これは遠洋性プランクトン有孔虫である *Globigerina* の遺骸を多く含むのでこの名がある. 珪藻軟泥は, 深層の養分に富む海水が上昇するため, 珪藻の繁栄を齎らし, かつ他の堆積物の影響を受けることの少い南氷洋や北太平洋の高緯度に広く分布する. 放散虫軟泥は北太平洋の低緯度に多い. 6000m 以深になると高水圧と低温のため, その溶解度が増加するので, 堆積物中の炭酸石灰 $CaCO_3$ の含有量は激減する(13).

なお大洋底にはこれら堆積物に混ってしばしば二酸化マンガン, 燐灰土, 灰十字石等の自生鉱物を産することがある. 海中風化等の産物である.

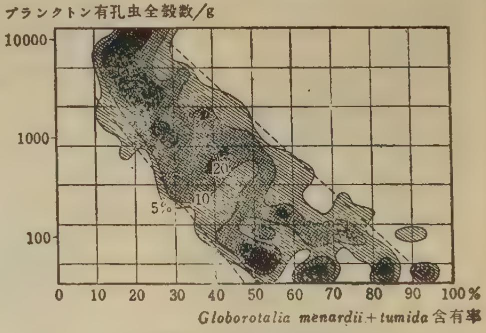
また深海堆積物の表面は通常正の酸化還元電位をしめすが, 数 cm 下ると負の値に変る. これにはバクテリアの作用が与って力あるものと考えられている(43).

深海底の堆積の速度を測定することは, 古くから種々試みられた. 例えば, (1) 第四紀の氷期と間氷期の気候的変化の影響を, 採集されたコアのプランクトン有孔虫や互層の垂直変化に対応させて, 各時期に相当する堆積物の厚さから割り出す方法(44)(45), (2) ウラニウム-イオニウム-ラジウム系列の放射能測定による方法(46)等でいずれも堆積物の表面近くで 1000 年につき数 mm から数 cm 程度の堆積が行われた, との結果を得ているが, 採集点の数の少いことと, コアの採集に際してその内容が多少とも圧縮されたものを補正計算の上にどのように反映させたか, という点に疑問が残されている. 最近は, (3) TiO_2 の堆積速度は生物的な影響を蒙らず一定とみなして差支えないとの仮定に立ち, これを時間の基準に採って, 石灰質堆積物中の C^{14} の放射能測定による方法(47)(48), が行われている. これにはピストンコアが使用されているので圧縮による誤差は余程少いと思われる. この結果もまた 1000 年につき数 mm から数 cm の堆積速度を示している.

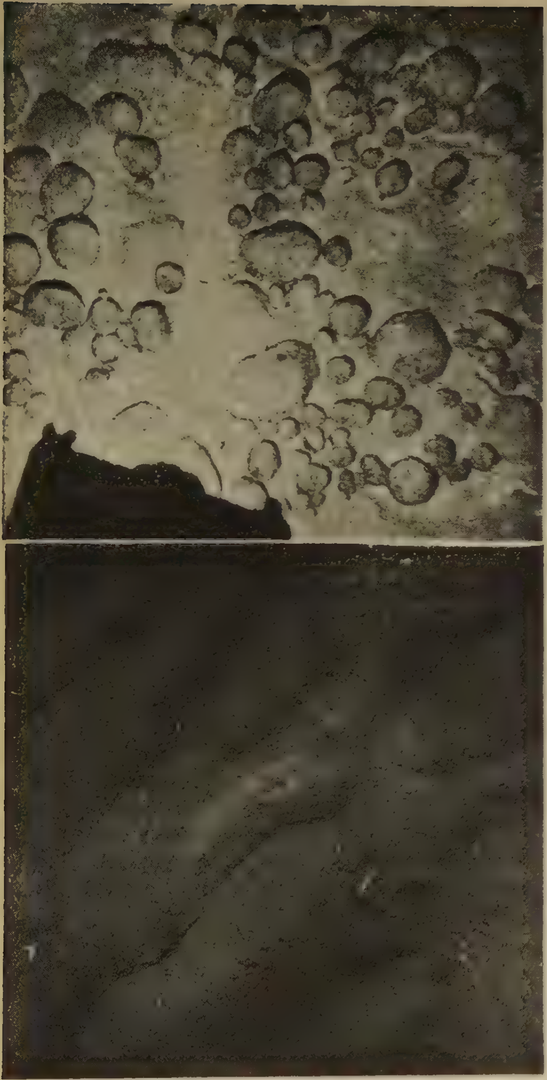
ピストンコアは 10 m 以上も海底に打込めるので, その下部は恐らく第三紀の堆積物にまで達するものと考えられる. 故に今後は単に第四紀の堆積速度や, その気候変化が生物相に及ぼした影響のみでなく, 第三紀の遠洋堆積状態をも明らかにしてゆくことが期待される.

第2次大戦前まで深海堆積物は薄い平均した厚さの層を成しているものと予想されていたが, その後行われた研究では, 堆積の速度および過程が時と場所により異ることを示し, 一概には律し得ないことが判明した(19). しかし, 数点の地震波探査の結果は, いずれも太平洋底において未固結堆積物の厚さが数百 m 程度で, また大西洋では 1km± 程度であることを示している(4)(5)(11)*.

いま少し深海堆積物の上に反映された古気候の状態について述べよう. **ARRHENIUS**(1952)(48)は東太平洋赤道附近の深海堆積物の研究に基いて次に述べるような興味深い結果を得ている. これら堆積物中のプランクトン有孔虫の含有量と, その中において暖海性有孔虫（*Globoro-*



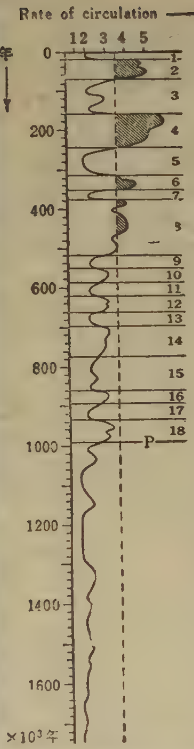
第12図　東太平洋赤道附近深海堆積物中のプランクトン有孔虫の総量に対し暖海性の *G. menardii*+*tumida* が占める比（ARRHENIUS(48)）



上：Bermuda 附近大西洋底の赤粘土中に横たわる manganese nodules　深度 5500m（海底写真としては最深のもの）（Woods Hole 海洋学研究所の D. Owen撮影）

下：Bikini 環礁近く Sylvania 海山の頂　深度 1370m. 底質はグロビゲリナ軟泥（H. W. Menard, R. S. Dietz 撮影）

talia menardii+tumida）の占める%との関係からは，有孔虫の含有量が多いときはむしろ寒冷な気候を示している（第 12 図）．これは他方また，高温の珪藻の生産とも比例している．彼はこの事柄を説明して――第四紀の氷期にはその寒冷な気候の影響を受けて貿易風帯は狭められ，かつその風力を増加したであろう．これは東太平洋赤道附近において養分に富む深層水の上昇を齎らし，これがため，海面近くプランクトン有孔虫や珪藻類は繁殖した．それらの遺骸は高い含有量として堆積物中に記録されている．しかし他方，暖海性の有孔虫の生産量は当然減少した．――と述べている．ただしこの仮説は東太平洋赤道附近に限定さるべきであり，他の海域ではまた別にそれぞれの事実に徴して適当な説明が附せらるべきであることを示唆している．これは大西洋やインド洋の堆積物について SCHOTT(44) 等が行った研究結果を考慮したのであろう**．ARRHENIUS は以上の考察に基き，TiO_2-C^{14} 法によるコアの分析結果から得られた時間の尺度を縦軸に，炭酸カルシウムの含有量その他を考慮した低緯度大気循環を横軸にとって第三紀後期，第四紀を通じての気候変化に対応させている（第 13 図）．



第 13 図　東太平洋低緯度の気候変化図

（Arrhenius(48)）黒色部は氷期に相当，P は第三紀末と第四紀の気候的境界

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* 地表の堆積岩は平均して火成岩の 3 倍の Ca を含む：すなわち堆積岩 1 を形成するために，少くとも火成岩3が侵蝕された結果となる．これは現在地表にある堆積岩の少くとも 2 倍以上に相当する堆積物が海中に留っていることを意味する．KUENEN はこのような観点から出発して，現在陸上にある堆積岩の約6倍が地質時代を通じて深海堆積は物として堆積を行ったはずであると仮定した．これ平均約 3km の厚さとなる(4)(13)．現在の堆積速度の推定値からすると，表面近く数百 m の厚さは，中生代後期以前には溯らない．もしこれ以上の量の堆積物が地質時代を通じて太平洋に降り注いだとすると，古い時代のものは未固結堆積物の中には既に存在していないことになる．大洋底の堆積物の厚さを地震波の伝播速度および反射から計算して数百 m と結論した最近の方法に対し，KUENEN自身は，その反射が果して堆積物と基盤の境から行われたものかどうかも疑わしいとしている(50)．もとより KUENENの始めの仮説は，地質時代を通じて火成岩の組成は大差なかったことを前提としている．

一方 UREY(1951) は海水中の O^{18}/O^{16} 比は水温の函数であり，生物が $CaCO_3$ の殻を構成する際にもこの比率はそのまま採用され，しかも後，変化をきたすことがないので，殻の中の O^{18}/O^{16} 比を調べることによって，棲息当時の水温を推定できるとした．これは化石による古気候研究上に定量的方法を導入したものといえよう(51)(52)．WISEMAN(1954)(53)は大西洋南赤道海流の下に横たわる深海堆積物表面のプランクトン有孔虫について O^{18}/O^{16}比からその生成時の水温を推定することをUREYに委託した．その結果は *Globigerinoides sacculifera*：23.5°C，*Pulleniatina obliquiloculata*：21.5°C，*Globorotalia menardii*：18.6°Cを示している．実際の表面水温は 26°±2°C であり，90〜100 m ほど下ると 15°C 程度であるから，これは *G. sacculifera* が後二者よりもさらに海面近くに分布しているものと解釈している．O^{18}/O^{16} 法はこのように深海堆積物についてはその表面に適用されたばかりであるが，将来，プランクトン有孔虫のみでなく，底棲有孔虫にも適用することにより，第三紀，第四紀の表面水温変化や底層水の水温を定量的に知る上に有効な手段となるであろう．

深海底（遠洋の深海に限らず陸岸近くの深海も含む）から折々砂質の存在が報告されることがある(54)(55)（~~写真上~~）．もちろん統計的な観点からすればその占める面積は微々たるものであるが，その地質学的意義は無視し得ない(56)．これが現地で形成されたものか，あるいは陸岸から遠く運ばれたものかとの点に関し論争が行われつつあるが，乱泥流あるいは海底地辷りによって浅海堆積物が深海底まで運搬されたとする説の方が有力である．PHLEGER(57)は浅海性底棲有孔虫がこのような深海の砂質の中に混入する事実をあげてこれを支持している．

やや本論の主旨から外れるきらいがあるが，乱泥流が維持されうる傾斜の限界について私見を述べたい．

その存在は実際に海底下で確められていないが，KUENEN の実験では，乱泥流は非常な速度に（100km/時を越えることすら予想される）達することがあり，上部の海水とは判然と区別され，その中での浮力は大で，粗粒の物質をも懸濁して高い密度を示し，遠距離を移動するという(20)(58)(59)．密度の異る二つの流体層が隣り合う場合，その境界面に沿って刺激を与えると内波が発生するが，これを乱泥流の場合に当てはめると内波は一般に

$$C=\frac{\sigma}{K}=\frac{\rho u+\rho' u'}{\rho+\rho'}\pm\left\{\frac{g}{K}\cdot\frac{\rho-\rho'}{\rho+\rho'}-\frac{\rho\rho'}{(\rho+\rho')^2}(u-u')^2\right\}^{\frac{1}{2}}$$

C：内波伝播速度，u, u'：下層，上層流体の速度，ρ, ρ'：下層，上層流体の密度，$\sigma=2\pi/T$，$K=2\pi/L$，T：内波の周期，L：内波の波長，g：重力の加速度．

右辺の右項の中が負となれば C は虚数となる．これは２層の境界面が不安定となり，もはや，上層と下層に分離しては存在し得ず，その間に渦が発生して混合現象の起ることを意味する．ゆえにいま乱泥流の速度を u，海水のそれを $u'=0$ とすれば，

$$u^2>\frac{g}{K}\cdot\frac{\rho^2-\rho'^2}{\rho\rho'}$$

のようになったとき，乱泥流と海水との間の安定は破れて，混合が起る．これは，泥質が上部の海水中に懸濁され，底に沿っては砂質より粗粒の物質しか残らないといった結果を齎らすであろう．上述の式は水平方向に対するものであるから，乱泥流が沿って流れる傾斜の影響を補正して計算する必要があるが，本質的に，これは，乱泥流の先端においての障害物の存在による擾乱その他の可能性を除外してただ単に底面に平行な境界面の条件のみを考察してさえ，乱泥流が長距離の移動を移持するためには，その速度に上限が存在することを意味する(61)．速度を支配する要素の中最大のものは密度と斜面の傾斜である．故に斜面がある値を越えて傾斜を増すと，速度が限界値を越えるので，もはや乱泥流としては存在し得なくなると考えられる．一方，傾斜があまりに緩やかすぎても砂質等粗粒の物質は沈積してしまうであろうから，これまた乱泥流としては存在し得ない．故に速度の下限も劃し得よう．かく乱泥流を維持しうる傾斜には上限，下限の存在が予想される．ただしその値は，堆積物の粒度分布その他の要素に支配されるであろうから場所により異ることは当然了解される．傾斜が上限を越えると泥質は次々とその位置で上方の海水中に懸濁されて移動せず，砂質のみが移動するような現象が期待される．これには一般に海底地辷りの名が適当であろう．もとより乱泥流も海底地辷りの一型式と考えて差支えない．

以上の考察では，不連続面に沿う内波の発生およびこの面と底面との平行性を前提条件として仮定している．将来の実験と観察に俟って，より実際と合うように修正を施すべき部分であろう．また実際問題としては乱泥流の先端の動向がその維持の上にもっとも影響を揮うことが予測されるし，今は乱泥流の厚さの全体に渉って一様な u の値を仮定しているが，これもまた実際の観察に俟たねばならぬ．以上は第一次近似にしかすぎず，将来より高次の近似が得られることを希望している．

海　　山

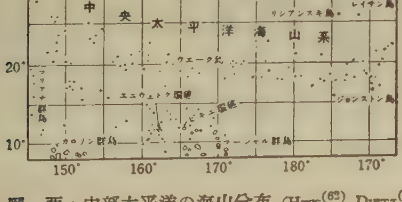
1946 年 HESS(62) は Hawaii, Mariana 群島間に分布する 160 余の海山の存在を報告し，これに 19 世紀の地理学者 Arnold GUYOT の名を冠して‘ギヨー’と名づけた．また彼は1941年に MURRAY(63) が指摘したAlaska 湾の海山も同性質のものであろうと示唆している．HESS が報告した海山は，多く中央太平洋海嶺に沿って分布するもので，Caroline 群島の北，Mariana 群島，火山列島の東に多く，それより西および南では同様の精

** WISEMAN(53) は大西洋での研究結果からプランクトン有孔虫の生産力を左右するものは養分よりもむしろ温度で，暖海では繁栄を齎すものとしている．

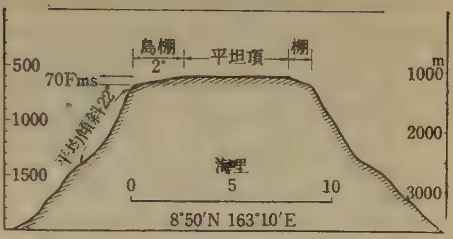
度の調査を行ったにもかかわらず発見できなかった．後，TOLSTOY(1951)(64)は大西洋で発見された Muir 海山について述べ，MENARD, DIETZ (1951)(65)は Alaska 湾の海山について詳細な報告を行っている．しかし以上はいずれも音響測深によって画き出された地形に基く報告であるが，1950 年 Scripps 海洋学研究所は中央太平洋海嶺に調査船を派遣し，海山の頂およびその附近から相当数の底質を採集した．その結果に基いて HAMILTON は報告を記し(66)，その一部を発表した(67)．これは海洋の歴史を解く鍵の一つを与えたものとして高く評価されている．なおその後も，北，中部アメリカの西海岸沖で幾つかの海山が見出されたし(68)，DIETZ は日本水路部との協同調査で，過去の海図に基いて東経 170° 線に沿って北太平洋をほぼ南北に走る海山の列を見出し，これを天皇海山系と名附けた(26)．昨秋 Baird 号がこの列を横切った際にも新たに一海山を発見し，聖武海山と命名した．天皇海山系はその南端において Hawaii 海嶺と接続している．海山は調査が進むに従い，今後も続々発見されるであろう（第 14 図）．

海山の地形的特徴は，(1) 円形か楕円形の平面図を画く，(2) 周囲の海底から普通 3000〜4000m 聳えている (3) しばしば平坦頂を持つ，(4) その水深は 1000m から 2000m の間に位置することが多い．(5) 平坦頂の周囲には 2〜3′ の傾斜を持つ島棚の存在をみることがある (6) 海山の規模は大小様々である．(7) 二三の近接した海山が同水準の平坦頂を持つことが折に見られる．(8) 頂は時によりやや波状を呈する等であろう（第 15 図）．

HAMILTON は五つの頂，およびその附近，並に一海山の麓から底質を採集しつぎの結果を得た．(1) 砂や礫が多い．(2) これらは主に olivine basalt の円磨された砂礫，それに二酸化マンガンの外皮を被るもの，また円磨された石灰粒の上を二酸化マンガンが被覆しているものから成っている．(3) これらは特に頂に近い斜面の表面に大量に存在している模様である．(4) 造礁性珊瑚の破片がしばしば採集された．(5) *Globigerina* を始めとしてプランクトン有孔虫が多く採集された．(6) その他の大型化石も多数採集されている．(7) この大型化石は白堊紀の Aptian から Cenomanian の暖浅海性を指示する．(8) 有孔虫もやはり白堊紀末期の示準化石に始まり，第三紀を経て現生のものまで種々存在する．(9) 白堊紀末を指示する化石は，当時の熱帯，亜熱帯を繞って広く分布していたと考えられる Tethys 海（古地中海）のそれで，現在相当する地表の推積岩中から得られるものに非常に類似している．これは白堊紀末の古地中海が Texas，中部アメリカを越えてさらに現在の太平洋中に数千浬延びていたことを示唆する（第 1 表）．



第 14 図　西・中部太平洋の海山分布（HESS(62), DIETZ(26)）



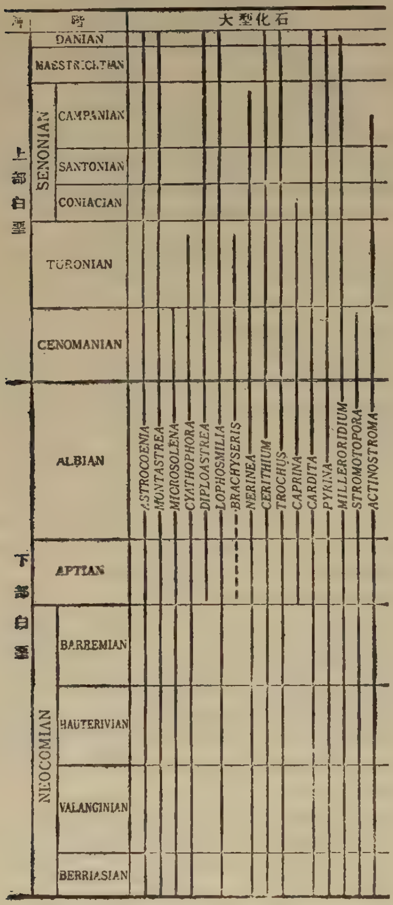
第 15 図　典型的海山の断面（HESS(62)）

以上の事実に基いて得られた推論は，(1) 多量に存在する円磨礫および頂の平坦部はこれがかつては波浪侵蝕によって形成されたものであること，(2) 化石もまた浅海性を示し，古気候は熱帯または亜熱帯であったこと，(3) 白堊紀末期の造礁性珊瑚の存在は当時この頂が海面近くに位置していたこと，かつ以後急速な沈降その他の理由によって環礁として成長する余裕がなかったことを物語る．

故に中央太平洋海嶺に沿う海山群の地史を綴れば——白堊紀には太平洋中の構造線に沿って噴出した玄武岩質の火山列島が形成されていた．波浪侵蝕はその頂を削り，平坦化し，島々は海面下にその姿を没した．温暖な気候は円磨礫の間に造礁珊瑚の棲息を許した．しかしアイソスタシー調整，その他の地下応力により白堊紀末の Aptian から Cenomanian の間に造礁珊瑚の棲息限界を越えて少くとも 100m 前後以上の急速な沈降が行われ，環礁形成の基盤は失われた．以来第三紀，第四紀を通じて沈降の傾向をたどり今日に到っている．その間遠洋性プランクトン有孔虫が絶えずその表面に降り注いだ．故に太平洋海嶺は海底に保存された世界最古の山脈の化石ともいえよう．以上が HAMILTON の結論である．

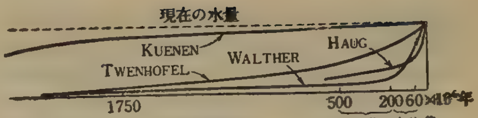
現在みる海山は平均して 3000m 程度周囲の深海底から聳えている．故に白堊紀末には太平洋の水深は少くとも 3000m を越えていたし，またそれ以来太平洋が深海盆としての存在を継続してきたことも理解される．しかしその間，さらに海山の頂と現海面との間に 1000m か

第1表　中央太平洋海山系より採集された大型化石
(Hamilton(66)未発表資料による)



ち 2000m の相対的な差を生じている．これが海山自体，あるいは附近の深海底の沈降に基くものか．白堊紀以後の海水量の増加に基くものか，あるいは両方の理由によるものかは，以上の発見された諸事実からは未だ解き得ない．第 16 図に示すように，地質時代を通じての海水量増加の過程に関しては，先カンブリア紀以来さしたる変化を認めぬ説から，白堊紀以後の急増を仮定する説まで種々唱えられている現状である．故に如上の点は全く今後に残された問題であるといえよう．

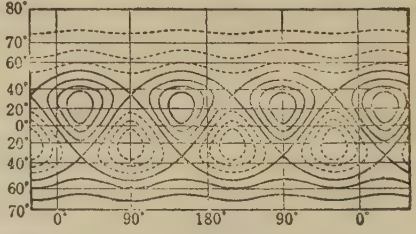
Marshall 群島中 Eniwetok 環礁のボーリング結果(69)は約1400mの深度を境としてその下にolivine basalt の存在を認め．その上は浅海性生物の遺骸を含む石灰岩層や石灰質砂岩から成ることを示し，また Bikini環礁についてもボーリングと地震波探査からおよそ同様のことが推定される(70)(71)．故に中央太平洋海山系以外の海域で熱帯あるいは亜熱帯に属して絶えず造礁珊瑚の棲息を許した場所には現在環礁が海面まで成長しており，Alaska 湾や天皇海山系のような高緯度の地方では造礁珊瑚の水平分布限度を越えるのでかつての侵蝕面が海山頂として保存されたものと解釈してよいであろう．



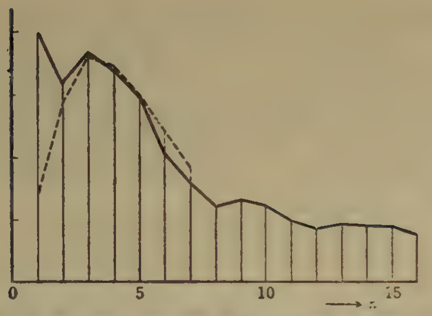
第 16 図　海水量増加の過程
(Kuenen(13), Umbgrove(6))

大洋底と大陸の起源

海洋底の起源ならびにその歴史を求めることは地学に課せられた根本問題の一つであり，大陸の生成過程とあわせ考究さるべきである．この問題に関しては 19 世紀後半から今日にいたるまで数多くの学者によって様々の新説が提唱され批判の対象となった．太平洋は月が地球から分離した際，地表に残した痕跡であるとする G. H. Darwin の古典的な説，大陸周辺を縁る海岸線の平行性と生物分布の様相から Wegener が提唱した大陸漂移説等(72)．しかしそれらのあるものはすでに否定され，その幾つかは疑点をはらんだまま残された．説，批判ともに事実に立脚しようとする努力は払われてきたが，資料が不十分であったのと，数理論的な根拠が薄弱であったため，いずれも仮説の域を脱却するまでには到らなかった．しかし約 10 年前よりオランダの Vening Meinesz は地球内部の熱対流の影響という観点から，理論的な背景に立って，この問題の解釈に努めつつある．注目に値する新説であると考えられる(73)．1944 年彼は大陸と海洋の分布に関する予報を発表し，つぎのように述べた(74)．地球が冷却を始めた頃中心の Ni-Fe コアと地表の間に熱対流が起り，2900km の深さに及び，その幅は深さの 2 倍に達したであろう．これは地表を八分し，その下に四つの下降流と四つの上昇流を形成した可能性

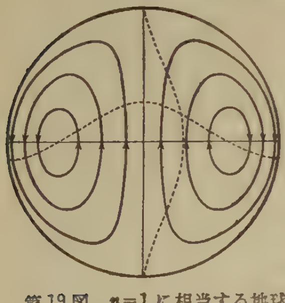


第 17 図　大陸と海洋底生成初期においての地球内部の熱対流分布図　実線：上昇流（または下降流），破線下降流（または上昇流）(Vening Meinesz(74))



第 18 図　地形を球函数に展開した各項の平均値
実線：地殻の厚さに相当する値．破線：温度分布に相当する値(Vening MEINESZ(78))

が最も大きい（第 17 図）．始めすでに存在していたシアルがこの四つの下降流の上に集められて大陸を形成したとしても，あるいは逆に上昇流が地表にシアルを分化し，それがそのまま固化して大陸を形成したとしても，現在の大陸と海洋底の対蹠関係，あるいは大陸が四面体の各頂点に位置する関係をよく説明できるとしている．1947 年同じくオランダの UMBGROVE はこの予報を引用して新説を発表した(6)．これはまた，次に述べる MEINESZ のより新しい説に吸収されているのでここには省略する．



第 19 図　$n=1$ に相当する地球内部の熱対流　破線は地軸に沿う速度分布とこれに直角な面を通過する速度分布 (Vening MEINESZ(78))

かつて PREY は長期に渉る労作の結果，地球上の地形を球函数に展開して係数の値を得た(75)．MEINESZ はこれをさらに検討し，1951 年彼の理論に新たな裏付けを行った(76)．翌 52 年にはその意見の一部を改めている(77)(78)．要約すると，第 18 図が地形を展開して得られた結果の一部であるが，$n=1$ に対する値が著しい．これは陸半球と海半球の存在を示す．$n=2$ から 6 に到る間の値は一つの波状を示し，これは現在の大陸と海洋底の分布に対応する．$n=8$ から 16 にいたる間さらに小さな波高の波が存在するが，これはより小さい規模の地形的特徴に相応している．一方，球体内で生起しうる対流系について温度分布を調べ，球函数に展開すると第 18 図の破線となる．これは地形においての実線と驚くべき一致を示している．この場合の $n=1$ は地球内部全体に渉る一つの大きな対流系に相当する（第 19 図）．これは計算の結果によれば，両半球に対称に分布する 2 対流系よりも起りうる可能性が大きい．$n=2$ 以上は地球内部に Ni-Fe の内核を想定し，その外側で対流系が起ったとして計算されたものである．ここにおいて MEINESZ は次のように結論した．

地球が冷却する過程において，まだ Ni-Fe の内核が形成される以前，冷却に伴う温度分布の差は一つの大きな上昇流と下降流から成る対流系を形成し，上昇流の上に分化したシアルは下降流の上に漂移して地表の 1/3 を覆うにいたった．陸半球と海半球の原形はかくて形成された．この対流はある期間の後減衰し，その頃地球内部には Ni-Fe の内核が形成され，一方表面の地殻はある程度の固化をみた．地表の 1/3 を覆う原大陸塊のシアルはその豊富な放射能熱によって地殻の下に幾つかの上昇流と下降流の分布を齎らした．このため，ある程度既に固化されていたシアルの層は分割されて再びそれぞれの下降流の上に集中し，四面体の頂点に位して海洋底との対蹠関係を作った．この際上昇流の中心には小規模のシアルの層が移動できなくて残されたであろう．これが中央大西洋海嶺や中央インド洋海嶺として大洋中に残されたシアルの痕跡であるのかもしれぬ．元来が海半球に属していた太平洋ではシアルの残る理由がなく，大規模な海嶺を形成する基盤がなかった．海洋底と大陸の原形はこのようにして完成された．その後地殻の固化は進み，大陸は地質時代を通じて大きな移動を行いえなかったと考えられる．WEGENER が指摘した各大陸周辺の平行性は合理的であり，大陸漂移の事実は起りえたであろう．しかしその時期は WEGENER が想定したような古生代以後ではなく，地殻の固化をみる以前の事柄であった．また，対流は週期性を持ち，その速度が年に数 cm 程度と考えられるから，一週期 3000 万年から 6000 万年，次の対流が起るまでの間に休止期が存在したとし，さらに地球の年令を 30 億年* と仮定すると，地球は 10 回から 15 回の対流輪廻を蒙ったことになる．これが造陸運動や造山輪廻と関連しているものと考えられる．そして現在，固化した地殻はもはや，移動を許さないが，大陸の下にはその放射能熱によって上昇流が存在し，これが海洋底の下へ流れ出ているものと考えられる．以上が MEINESZ の見解であるが，一方 JEFFREYS(80) も地球内の対流系を調べ，内核が存在しない際には $n=1$ に対し第 19 図に見る対流系が理論的に成立することを確めた．内核が存在する際には $n=3,4$ がもっとも強く現われるが，$n=1$ もまた刺激されるといっている．故に海半球と陸半球の成立は必ずしも内核形成以前でなくてもよく，内核形成後であっても $n=1$ に相当する長波長の刺激がこれを形成し，$n=3,4$ に相当する次の規模の海洋底と大陸の分布がこれに重って生じたとしてもよい，として余裕を残している．しかし彼もまた，大洋底と大陸の分布がほぼ完成されたのは地球が全く流動性を帯びてい

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* この年齢に関しては，数多くの説があるが(79)(80)，MEINESZ は仮に 30 億年と採ったにすぎない．

た頃でもなく，また全表面の固化が進んだ後でもなく，その間，固化の進む過程においてであった，とする点で MEINESZ，UMBGROVE と意見の一致を見ている．

なお 1947 年に MEINESZ(81) は地球表面の構造線に着目し，地軸の相対的移動が地殼に及ぼす剪断力を計算した結果 大陸や大洋底に存在する実際の主要構造線とほぼ一致する剪断面の網を得た．これは主として東北–西南と西北–東南の２方向より成る菱形網目である．この剪断網は大陸と海洋底の分布がほぼ完成した頃には形成され，以後の地殼変動や火成活動は，地殼の弱所であるこの網目に沿って繰返された可能性が大きいとしている．彼はさらに語をついで，地下応力のために次に起る可能性の強い剪断網はこの菱形と直角に交る東–西，南–北方向としている．このことは，その後追々と明らかにされつつある太平洋中の東–西，南–北方向の構造線と関連して将来の研究に一つの課題を提出しているように筆者には感ぜられる．

以上の解釈によると大陸性の地殼と大洋性の地殼の境界は地質時代を通じて水平方向には大きな移動を行っていないことになる．この問題と関連して，地向斜生成ならびに造山輪廻について一言触れたい．

古くより唱えられたことであるが，比較的新しくは，BORN(1933)(82)によって再認識された原大陸塊の周囲は造山輪廻によって次第に伸長しつつある——との考え方は今日なお多くの地質学者の支持を受けている．しかし KUENEN(13) はこれに対して疑問を提出し，(1) すべて地向斜の基盤が大陸性であること，(2) 真の遠洋性堆積物がかつて陸上の堆積岩中に見出された確証がないこと，(3) および地向斜堆積物はその両側に供給源を持っていた可能性が認められる，との３点を挙げて反対している．もとより，明白にそれとは指摘していないが，MEINESZ や UMBGROVE の新説を考慮に入れた上での反対であろう．

今ここで，大陸と大洋底の分布が MEINESZ–UMBGROVE の唱えるように先カンブリア紀初期にはすでにその原形の完成をみていた，と仮定してこの問題を振返ると，地向斜の形成ならびにそれに続く造山褶曲運動は大陸内部およびその周辺に限定され，地質時代を通じてほぼ同位置で週期的に繰返し行われたことになる．これは KUENEN の挙げた三つの事項を一応満足させる結果となる．この観点からすると事実大陸に囲繞され，その下に数千 m の厚さの堆積物を蓄えていると目されるメキシコ湾等，現成の地向斜と称しうるのかもしれぬ．

しかし２説の中，いずれが是なりと判断するにはまだ資料の集積が不十分のようである．両説を考慮に入れつつも捉われることなくより多くの事実の観察を行うことが肝心であろう．

以上の稿を草するに際して筆者は意識しつつ，海底地質学．それも主として海底地形学の立場から逸脱しないように努めた．故に小論では大洋底の生物学および地球化学的な研究については，その顕著な進歩にもかかわらず，ごく簡単にしか触れていない．また，日本周辺の海底状況について詳細に述べたい希望を持ちつつもかえってこれを避けた．祖国を遠く距った地にあって参考文献の使用が困難であったことと，筆者自身の未熟を省みて他日に期した次第である．

校閲をいただいた東京大学理学部坂本峻雄教授および Scripps 海洋学研究所の F. P. SHEPARD 教授に深甚の謝意を呈する．また，Dr. DIETZ, Dr. HAMILTON, Mr. FISHER を始めとして同研究所の方々に資料を提供していただいた．特に未発表の事項すら本稿のために発表を快諾された後の２人の方には，ここにその旨を記して謝意を表する次第である．

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STRATIGRAPHIC VALUE OF DISCOASTERS AND SOME OTHER MICROFOSSILS RELATED TO RECENT COCCOLITHOPHORES

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ABSTRACT.—Much scientific work has been done on Recent Coccolithophoridae and some fossil forms have been described, but little attention has been given to their value in biostratigraphy. Some largely extinct forms which may be closely related to these minute algae have been known under the generic term *Discoaster*. The systematic position of the discoasters is uncertain; originally Ehrenberg regarded them as inorganic "Crystalldrusen," but it is now evident that they are the skeletal remains of nannoplanktonic organisms. Despite the little taxonomic work done and the difficulties involved, present data indicate the probability that the discoasters, especially, may aid in world-wide correlation of certain Tertiary time horizons.

The very small (about 10 microns) calcareous remains of these organisms are common in some late Mesozoic and Tertiary rocks, particularly in those of open-sea deposition, and constitute the main bulk of some chalky sediments. Distinctive forms characteristic of certain parts of the Tertiary are found on both sides of the Pacific and Atlantic oceans, including the Caribbean and Mediterranean regions, and elsewhere. Some of these are described and some data presented on their stratigraphic distribution.

INTRODUCTION

THIS investigation was initiated during the microscopic examination of the fine constituents of bottom sediments from the Pacific Ocean. It was noted that the assemblages of coccoliths and other minute calcareous skeletal remains in certain cores which penetrated Tertiary strata were strikingly different from those of the Recent sediments of the region. Examination of available Tertiary calcareous rocks of reasonably well-established age revealed many equally abundant and distinctive assemblages. Nearly three hundred Tertiary and some Cretaceous samples from various parts of the world have been examined thus far, and the wide geographic distribution of some of the forms is impressive.

This report must, however, be considered as preliminary, as only some of the more distinctive forms have been studied, and adequate checking of their occurrence is far from complete. Nevertheless, the data now available indicate the real value of these microfossils in biostratigraphy and seem adequate to show tentative age ranges of certain distinctive forms, which will probably not be very greatly modified with additional data.

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The many samples have been obtained from so many sources that acknowledgments can hardly be given here. Many foreign laboratories of oil companies, universities, and government agencies have kindly supplied material along with the best available data on their age.

The coccolithophores, which form an important element of the oceanic plankton at the present time, have been intensively studied. These biflagellate protists occur in vast numbers in the near-surface waters of the open oceans, and a few species are known from brackish and even fresh waters. The complete skeletal remains usually have a spherical or roughly spheroidal form, but these coccospheres are so fragile that they are much less common in bottom sediments than the disaggregated tiny plates called coccoliths. Classification of the living forms is based largely on the calcareous hard parts.

Many papers are available on the Recent coccolithophores. This paper, therefore, is concerned largely with some related forms—particularly with those included under the "form genus" name *Discoaster*. The organisms responsible for the formation of skeletal remains classed as discoasters are not known to be living at present and there is therefore no certainty of their close relationship to the typical coccolithophores. Indeed some doubt exists that discoasters represent the remains of a single-celled organism—plant or animal—as indicated in the subsequent discussion of taxonomy.

The fossil forms, especially of the coccoliths, constitute a major part of some chalky formations of the Cretaceous and Tertiary, and are common in many calcareous shales. Few, or none, are found, however, in other fossiliferous marine strata that seem to represent less open sea conditions. Thus Tertiary sediments containing Globigerinas or other pelagic Foraminifera are apt to contain many coccoliths as well as other planktonic forms such as *Discoaster*.

Occurrence of such minute calcareous forms is limited also by the degree of lithification and recrystallization of the rocks. Any such forms are apt to have been obliterated in hard limestones. Even in fine-grained limestones, where recrystallization is less advanced, the extraction and identification of any remaining forms is difficult.

Type specimens will be deposited in the U. S. National Museum, Washington, D. C.

PREVIOUS WORK

Ehrenberg (1836) first mentioned the small ovoid bodies occurring in the chalk, but considered these coccoliths to be of inorganic origin. Huxley (1858) noted their presence in Recent oceanic sediments and applied the name "coccolith." Sorby (1861) showed that coccoliths were derived from small hollow spheres, and that those of the chalk were not inorganic but similar to Recent coccoliths; he evidently examined the Recent forms and came to this conclusion without knowledge of Professor Huxley's work.

The more intensive work, including systematics, came much later, beginning with Lohmann (1902), followed by Schiller (1930), Kamptner (1941), and others.

Ehrenberg was likewise the first to note the small stellate bodies now known as discoasters, and several were figured in his great volume "Mikrogeologie" (1854, pls. 24 and 25), though he considered them inorganic calcareous "Crystalldrusen." He had earlier (1844) described some rather similar forms under the generic name *Actiniscus*, but evidently recognized their opaline composition and included these along with diatoms in his Polygastrica.

Jukes-Brown and Harrison (1892, p. 178) figured several such calcareous "stellate bodies" from the Oceanic formation of Barbados. The first systematic work was by Tan Sin Hok (1927), who applied the name "Discoaster" to the group and briefly described, with figures, several species and varieties from the late Tertiary of Indonesia. A few forms were described by Sujkowski (1930) from Poland, and by Bersier (1939) from the Molasse of the northern Alps. It seems probable that Bersier's specimens were reworked from older strata because of the rarity of specimens, their similarity to earlier Tertiary forms and their occurrence in apparently non-marine Molasse. Parejas (1934) described some specimens from the Upper Cretaceous which resemble *Discoaster* in form and size. These had a siliceous composition, however, and were therefore included in Ehrenberg's genus *Actiniscus*. Colom and Gamundi (1951) figured several forms of *Discoaster* from the middle Tertiary of Majorca, and identified them under names applied by earlier workers. Most of the work since 1934 has been by Deflandre, and is summarized with his views on their systematic arrangement in the Traité de Paléontologie (1952a) and more completely in the Traité de Zoologie (1952b).

METHOD OF STUDY

Vast numbers of coccoliths, discoasters, and other related forms occur in the fine-grained calcareous sediments of the present ocean bottom and in many chalky rocks of the Tertiary and Cretaceous. A few cubic millimeters is thus an adequate amount of many such rocks. Boiling of the sample will usually disaggregate sufficient fine material that can be decanted onto a microscope slide and dried. Canada balsam or other mounting medium and a cover glass complete this simple preparation. Moving the cover glass over the viscous Canada balsam permits varied orientations of the minute specimens, and a permanent mount may be prepared subsequently by slow cooking of the preparation.

Microscopic examination at magnifications of 400 to 500 diameters seems adequate for discernment of the distinctive features of the discoasters and some coccoliths, though higher magnification with an oil immersion lens is helpful, and in some cases necessary. A phase-contrast microscope which permits continuous variation through different conditions of illumination is very useful, as certain details appear best under different phase-contrast conditions between the dark-field and normal illumination. This is particularly important because of confusing effects commonly caused by much refraction in normal illumination. A universal stage for various orientations would be valuable, if adequate magnification were possible with this accessory.

Discrimination of important characters of the coccoliths, especially of those less than 5 microns in diameter, is more difficult, requiring high magnification and preferably supplemented with observations under polarized light. Kamptner (1952) has found remarkable and distinctive characters in the arrangement of the calcite micelles forming the structure of different types of coccolith. The orientations of the minute micelles of the fibrous structure are determinable, even under high magnification, only because of the high birefringence of calcite under crossed nicols. The electron microscope is also proving valuable to the specialists working on the coccoliths. Such elaborate methods of study are important to taxonomy, but the usefulness of such discrimination among the smaller coccoliths is limited in stratigraphic work, because the determination of their distribution in space and time requires the examination of such a great number of specimens from many samples. Only two coccoliths of unusually large size are preliminary described in this paper.

Photography is, unfortunately, not very satisfactory for reproducing these small objects, as depth of focus is insufficient at the required magnifications. Drawings are required to reproduce features which can be discerned only by varying the focus and the phase-contrast lighting.

MATERIAL STUDIED

In addition to the many Recent and some Tertiary samples from the ocean bottom, nearly 300 surface samples from many parts of the world have been examined to date. None of these samples has been thoroughly studied, however, and only some of the more easily differentiated forms, including most of the distinctive discoasters, are considered here. Most of the samples selected are from strata of reasonably well established age.

Relatively few samples of Cretaceous age have been examined, as forms identifiable as *Discoaster* are rarely if ever present, though coccoliths are abundant and of great variety. Very few data are now available on Pliocene occurrences, as samples from an open-sea environment with considerable pelagic elements seem strangely uncommon in identifiable Pliocene strata. Many good samples from Miocene strata are available from countries of the Mediterranean, Caribbean, and Pacific borders. Available samples from Oligocene strata are largely limited to the Caribbean region. The largest number of samples are from different parts of the Eocene from many parts of the world, and these contain the most abundant and distinctive assemblages. Fewer samples, but from widely separated parts of the earth, are available from the Paleocene.

BIOSTRATIGRAPHIC CONSIDERATIONS

The available data on their distribution in space and time indicate that, among these small planktonic organisms, at least the discoasters can be used in attempts to correlate strata—and they are perhaps more useful for interregional correlation than for the correlation of local units of short duration. Because of the relatively limited number of distinctive forms of *Discoaster*, it is doubtful that these alone could be used for local subdivision of minor stratigraphic units in the same manner as are the Foraminifera. Assemblages which include many forms having different but in part overlapping time-ranges are obviously more reliable age-indicators than individual "guide-fossils," but *Discoaster lodoensis* is an example of a species which may prove useful as a guide-fossil. This species has been found in the Capay (lower Eocene) of California, in the Ramdat (lower Eocene) of Trinidad, in the basal shale of the Plaisance limestone (middle Eocene) of Haiti, and in strata classed as lower Lutetian (middle Eocene) of Donzacq, France. It has not yet been found in strata of earlier or later age, and thus seems to be widely distributed in the lower Eocene and the lower part of the middle Eocene. Only their value in age assignments can be considered at this time, as the following few remarks indicate the little present knowledge bearing on ecologic and other aspects in stratigraphy.

These small planktonic organisms are presumably subject to fewer or less complex ecologic controls than benthonic organisms. Only a few forms, and these of the typical coccolithophores, are known to exist in fresh water, and some others in brackish water, but an abundance of varied forms is characteristic only of the open oceans. At least those known to be algae would be largely limited to near-surface waters, and so their distribution is probably affected by the near-surface temperatures. Lohmann (1902, pl. 6) shows the coccolithophores at one station in the Mediterranean to be largely limited to depths above 150 meters, and the great abundance to depths of 25 to 75 meters. Bernard (1948) reported *Coccolithus fragilis* Lohmann as abundant down to depths of 1000 meters in the Mediterranean, but apparently he did not determine that the cells were actually alive at such depths. Moreover, the compensation depth for general phytoplankton is 100–150 meters in the very clear water of the Sargasso Sea (Riley, 1939, p. 153), and it is likely that the water of the western Mediterranean is not so clear and that therefore there would not be enough light for the growth of coccolithophores even at 150 meters at Bernard's localities. Though some coccolithophores are known from Arctic waters, most of them occur in temperate or tropical waters—especially such forms as *Rhabdosphaera*. The abundance, large size and variety of forms in the Eocene may reflect the generally warmer oceans of that time.

Nothing is known yet about ecologic controls which affected such largely extinct groups as that including *Discoaster*. The former occurrence of species over widely separated parts of the earth suggests, at least, that prohibitive controls were not common, though data from high latitudes are not available.

Records of coccoliths before Jurassic time seem doubtful, and only beginning with the Cretaceous are vast numbers found in the rocks. Because of their extreme delicacy and the consequent tendency for corrosion or secondary growth during lithification to limestones, it seems possible that they developed much earlier than Jurassic time, but have been largely obliterated in earlier strata along with the conversion of any chalks to fine-grained limestones.

Forms referred to *Discoaster* have been reported from the Cretaceous, but we have been unable to substantiate such pre-Tertiary occurrences and have not found them in the considerable number of samples examined. The only possible exceptions are in samples such as one from the Velasco shale of Mexico, which is considered either Paleocene or uppermost Cretaceous (Danian). Ehrenberg (1854, pls. 24 and 25) figured specimens of what appears to be *Discoaster barbadiensis* from "Kreidefelsen" of Egypt and Antilebanon. Other constituents of these samples, including the Foraminifera, are quite different, however, from those of his samples of "Kreidefelsen" which are known to be Cretaceous chalk, and none of the latter show forms resembling *Discoaster* though coccoliths are abundant. Early Tertiary chalk and marl are now known to occur also at the poorly defined locality of Thebes in Egypt and in Antilebanon, and it seems probable that these "Kreidefelsen" samples were post-Cretaceous. Certain forms described by Sujkowski (1930) apparently came from the Cretaceous of Poland, but those resembling Tertiary discoasters were only one-fifth the size of known discoasters, and such forms are as yet unknown elsewhere.

The latest occurrence of *Discoaster* is likewise open to some doubt. A plankton catch from the Mediterranean contained a single specimen that was named *D. planktonicus* by J. Lecal (Archives de Zoologie, 1952). This specimen of spherical form (about 30 microns in diameter) had many stellate objects on the surface but it was stated that these elements seemed to be of "amorphous" material under polarized light rather than calcite. No examples, with the possible exception of rare *D.* aff. *D. aster* (see p. 400), have been observed by us in the many Recent samples, except where there was other evidence indicating reworking or where such derivation could be expected. A supposed Recent occurrence was recorded from a South Atlantic bottom sample, *Challenger* Sample No. 338, first figured in the *Challenger* volume on Deep Sea Deposits (Murray and Renard, 1891, pl. 11). One of these figures was taken by Tan Sin Hok as representing the type of his *D. molengraaffi*. Dr. Ovey of the British Museum kindly sent us part of this original sample, and several different forms identical with those of the Miocene were found, but they were very rare among the abundant coccoliths and other skeletal remains of Recent aspect. Because of the irregular bottom topography and proximity to the mid-Atlantic Ridge, it seems probable that here as in some areas with substantiating evidence, the specimens of *Discoaster* were derived from Tertiary deposits which locally slumped, along with the thin cover of later deposits, from a steep slope of the sea-floor. The minute size of these fossils permits them to be transported much farther than Foraminifera, as the latter are many thousand times greater in bulk.

Only some of the more common and widely distributed forms of *Discoaster* are described in this paper, and some data on their distribution in the Tertiary are given. Perhaps an equal number of distinctive forms have been observed, but remain to be described after compilation of additional data on their variations and distribution. It is evident, however, that the number of "species" of *Discoaster* is less than that of typical coccolithophores.

The wide geographic distribution of many species is evident. Some general data on their occurrence in time are indicated with their descriptions, but no attempt at a precise age range of the described forms is justified at present. *Discoaster barbadiensis* is indicated as common in samples throughout the Eocene, but we have not attempted to discriminate closely within this "form species." It seems to terminate rather abruptly, as it has not been observed in samples classed as lower Oligocene, though most such samples are available only from the region of middle America. An interesting example of its upper limit of range is found in a sequence of 38 samples of the Oceanic formation from Bath, Barbados. *D. barbadiensis* is very common in the lower 30 samples and absent in the upper eight samples. The upper part of the Oceanic is considered Oligocene by Senn (1940) and others who have studied the foraminiferal faunas. The change in the radiolarian faunas which the junior author considers to indicate an Eocene-Oligocene boundary is found between two samples separated by only a few meters of strata. Surprisingly, the change in the discoaster assemblage occurs between these same samples—with the dropping out of the common *D. barbadiensis*. Perhaps this reflects some change in the surface waters, as a considerable hiatus or other discontinuity would not be expected in the rather uniform Oceanic formation of relatively deep water deposition.

Most strata of Oligocene age seem to have a much less varied assemblage of discoasters and coccoliths than those of the Eocene, but a number of new forms appear in the Miocene. The phylogenetic relationships of the distinctive Miocene forms are obscure. The approximation to synchrony of their appearance within the middle Tertiary of many parts of the world presents an interesting problem. They occur in the few samples examined from the middle and upper Miocene of the Mediterranean region, but not in samples from the Aquitanian and Burdigalian of the Aquitaine basin. The few available samples which can reasonably be considered as typical Burdigalian do not contain a good discoaster assemblage, but the one species present is one common in the Oligocene. In the Caribbean region, a corresponding change from the forms characteristic of the Oligocene and lower Miocene (Burdigalian) of Europe to the distinctive ones of the upper Miocene of Europe is very striking. In the many samples from the Caribbean region, however, the change occurs between strata classed as middle Oligocene and those generally classed as upper Oligocene. This same change occurs in some samples from Indonesia which had been assigned to the upper part of the Tertiary east of that region.

Much additional study of the discoasters, coccoliths, and related forms is needed before any such biostratigraphic relations can be established, and any time-stratigraphic significance must be evaluated with reference to other paleontologic evidence. Both theoretical and observational considerations suggest, however, that these planktonic organisms may be more widely and quickly distributed over the oceans than most other organisms.

These small fossils are commonly only 3 to 15 microns in diameter and thus near the size limits between clay and fine silt particles. Erosion and transportation may thus distribute them widely and produce a serious problem of reworked specimens. Although reworking of microfossils (e.g. Foraminifera and Radiolaria) is not uncommon, it is usually not justifiable to explain unexpected stratigraphic occurrences as being due to reworking, unless other evidence supports such an interpretation. Supplementary evidence of the reworking of coccoliths and discoasters is common enough, however, to indicate that these microfossils are reworked more commonly than are many other fossils.

One good example of reworking is evident in the core MP 27 from the Mid-Pacific samples described by Hamilton (1953). Slumping from a nearby guyot produced a sediment with a mixed assemblage of Recent, middle Tertiary, Paleocene and Cretaceous Foraminifera. The fine fraction of this sediment contains also an anomalous mixture of discoasters. Characteristic species of Foraminifera were selected and crushed individually, and the assemblages of discoasters and coccoliths from within the chambers were correspondingly distinct. The Paleocene form, *Discoaster multiradiatus*, was common from within chambers of *Globorotalia velascoensis*, middle Tertiary forms such as *D. brouweri* and *D. challengeri* were common in specimens of *Globigerina altispira*, and distinctive Cretaceous coccoliths without discoasters were found in specimens of *Globotruncana arca.*

An Oligocene marl from Mariel, Cuba, offers a similar example, where a considerable number of discoasters normally occurring in the Eocene are found together with the more numerous Oligocene forms. Rare specimens of such characteristic Eocene Foraminifera as *Hantkenina alabamensis* and *Globorotalia cerro-azulensis* were found among the abundant Oligocene Foraminifera. Crushing of the thoroughly washed Eocene specimens showed Eocene discoasters, and quite a different assemblage was found in crushed specimens of the common Oligocene Foraminifera.

Because of their very small size, some reworked specimens may be expected rather commonly even though Foraminifera and larger fossils were not transported equally far from the source. Several samples from the Miocene of Haiti thus show some specimens of various Eocene discoasters and coccoliths, though reworked Eocene Foraminifera were not found. A similar derivation from the Eocene is believed to explain the recorded occurrence by Colom and Gamundi (1951) of *D. barbadiensis* in the Aquitanian-Burdigalian strata of Majorca. Samples kindly supplied by Colom show this form to be uncommon among the abundant middle Tertiary assemblage. It seems probable that such widespread and common forms as *D. barbadiensis* will be found reworked in later sediments so commonly that the actual life span may appear very doubtful. This form, so abundant in the Eocene, seems to be entirely absent, however, in the post-Eocene strata of many places where there is no evidence of other reworked elements. The available data thus indicate that *D. barbadiensis* lived only during the Eocene, and sporadic occurrences in strata of later age should be considered carefully for other evidence of derivation from reworking of Eocene material. The evidence of reworking is thus found commonly enough to require serious consideration in biostratigraphic interpretations from all of these exceptionally small fossils.

TAXONOMY

The systematic classification of fossil coccoliths, discoasters, and similar forms is beset with even more difficulties than are associated with that of most other groups of fossils. Apart from the lack of knowledge of the soft parts of some of the organisms, the problem is complicated by the dissociation of the skeletons into isolated skeletal parts, as with most coccoliths and all discoasters. In the case of the coccoliths, the forms which are still living give some indication of the methods to be applied in the classification of the fossil forms, but *Discoaster* apparently has few or no close relatives living, and although *Braarudosphaera*, *Thoracosphaera*, and *Ceratolithus* are evidently now living in the oceans, we have no knowledge of their soft parts.

A review and revision of the classification of all of these organisms and their isolated skeletal parts was presented by Deflandre (1952b). He grouped all of the forms dealt with in this paper into the class Coccolithophoridés of the Flagellata, although pointing out that there is little real evidence to justify the inclusion of *Braarudosphaera*, *Thoracosphaera*, and the discoasters. He divided this class into two orders, on the basis of the microstructure of the calcite of the skeletal parts: the Heliolithae (including all the coccoliths; tremaliths, rhabdoliths and lopadoliths), the skeletal parts of which have a radiating-fibrous structure, and the Ortholithae (including *Thoracosphaera*, *Braarudosphaera* and the discoasters), in which the skeletons or larger parts thereof have the optical properties of single crystals. Subdivision of these two orders was based on general morphological characters.

The skeletal structures of Deflandre's group Heliolithae include the common forms of coccoliths (simple or double, circular or elliptical calcareous plates often bearing some type of ornamentation), and other distinctive forms of coccoliths such as rhabdoliths (small plates surmounted by long hollow rods of various types) and lopadoliths (varying in shape from short, barrel-like to long and tubular). In some living members of this group, two different types of these skeletal elements are present on the same individual.

As this order (Heliolithae) contains many living forms, it has been divided by a classification based in part on the structure of the entire skeleton. Because of the dimorphism of the skeletal elements of some members of this group, the fossil remains, occurring usually as isolated parts, cannot be classified according to such a system, and therefore Deflandre and Deflandre-Rigaud have proposed an artificial classification of the isolated skeletal parts into manipules and centuri instead of genera and species, along the lines suggested by Croneis (1938).

Only two unusually large and distinctive coccoliths are described in the present paper. The form which we describe as *Coccolithus grandis* has been figured as a complete coccosphere by Deflandre (1952b) and thus it can be referred with some certainty to the genus *Coccolithus*. The other is assigned only to a manipule (*Tremalithus*), because we do not know the nature of the complete skeleton.

COCCOLITHUS GRANDIS Bramlette and Riedel, n. sp.

Plate 38, figures 1a, b

"Coccolith," JUKES-BROWNE and HARRISON, Quart. Jour. Geol. Soc., vol. 48, p. 178, fig. 7, 1892.

Coccolithus cretaceus Archangelsky of DEFLANDRE, Traité de Zoologie (ed. P.-P. Grassé), vol. 1, fasc. 1, p. 463, fig. 360 D, 1952.

Placoliths unusually large, consisting of two curved plates, of which the lower is nearly as large as the upper. The two plates are so closely appressed that it is impossible to see the connecting tube in side view. A large part of the central area of the placolith is occupied by an X-shaped cross, which can be observed on both surfaces of the placolith as it bridges the large central opening. The calcite of this cross acts optically as a single crystal, in contrast to the fibrous structure that is usual in coccoliths. Very fine striae are observable on the border of both plates. Major diameter usually 18–23 microns.

This species resembles the older *C. cretaceous* Archangelsky, which is consistently much smaller.

Type locality.—Scripps Mid-Pac Core No. 25 E-1 (Lat. 19° 40′ N., Long. 168° 32′ W., depth 931 fm.).

Other occurrences.—Lower part of Oceanic formation (Eocene), Mt. Hillaby, Barbados; lower Lutetian, Donzacq (Landes); Lodo formation (Capay stage, lower Eocene); Lodo Gulch, Fresno County, California; also at many other widely scattered Eocene localities.

Discussion.—This form is common in the Eocene, particularly in the middle and lower Eocene. Its upper limit is uncertain, but it is much less common than *Tremalithus eopelagicus* in the upper Eocene.

TREMALITHUS EOPELAGICUS Bramlette and Riedel, n. cent.
Plate 38, figures 2a, b

"Coccolith," JUKES-BROWNE and HARRISON, Quart. Jour. Geol. Soc., vol. 48, p. 178, fig. 8, 1892.

Placolith unusually large, elliptical, consisting of two curved plates of which the lower is slightly smaller than the upper. The plates are rather closely appressed, and therefore the thick-walled connecting tube is visible in side view only through the thin, curved edges of the plates. In surface view the plates show an elongated central slot and, peripherally, fine curved radiating striae. Major diameter usually 16-20 microns.

This placolith is larger than any other described form, except for the distinctive *Coccolithus grandis*, with which there are otherwise no similarities. Consistently smaller forms rather similar to *T. eopelagicus* are found in middle Tertiary and later strata.

Type locality.—Middle of the exposed Oceanic formation at Bath, Barbados.

Other occurrences.—This form is very common in the middle Eocene through lower Oligocene from many parts of the world.

No attempt is made in this paper to discuss the Tertiary rhabdoliths, lopadoliths and other types of coccoliths. However, when more work is done, they may prove useful stratigraphically. Among other rhabdoliths one large form (pl. 38, fig. 3) has been noted commonly in early Tertiary strata: this form may be closely related to *Rhabdolithus perlongus* Deflandre (1952b, fig. 362 I, from the Lutetian, figured without description or dimensions).

Some of the early Tertiary rhabdoliths, such as that figured (pl. 38, fig. 3), do not show the parallel extinction under crossed nicols which Kamptner (1952) found in the

EXPLANATION OF PLATE 38

All illustrations ×2500.

FIGS. *1a*, *b*—*Coccolithus grandis*, n. sp. *1a*, vertical view of holotype; *1b*, sketch of slightly oblique lateral view. (p. 391)

2a, *b*—*Tremalithus eopelagicus*, n. cent. *2a*, vertical view of holotype; *2b*, sketch of lateral view showing an optical section. (p. 392)

3—Large rhabdolith from the upper Eocene near Isney, Alabama (same as type locality of *D. tani nodifer*). (p. 392)

4—Lopadolith from Miocene marl, 1.6 miles S of Mafron, Haiti. (p. 393)

5—*Thoracosphaera* sp., Cipero formation (upper Oligocene), Retrench Quarry, Princes Town area, Trinidad. (p. 393)

6a, *b*—*Braarudosphaera bigelowi* (Gran and Braarud), Lodo formation, 135 ft. above base (lower Eocene), Lodo Gulch, Fresno County, California. *6a*, vertical view of isolated pentalith; *6b*, sketch of lateral view. (p. 393)

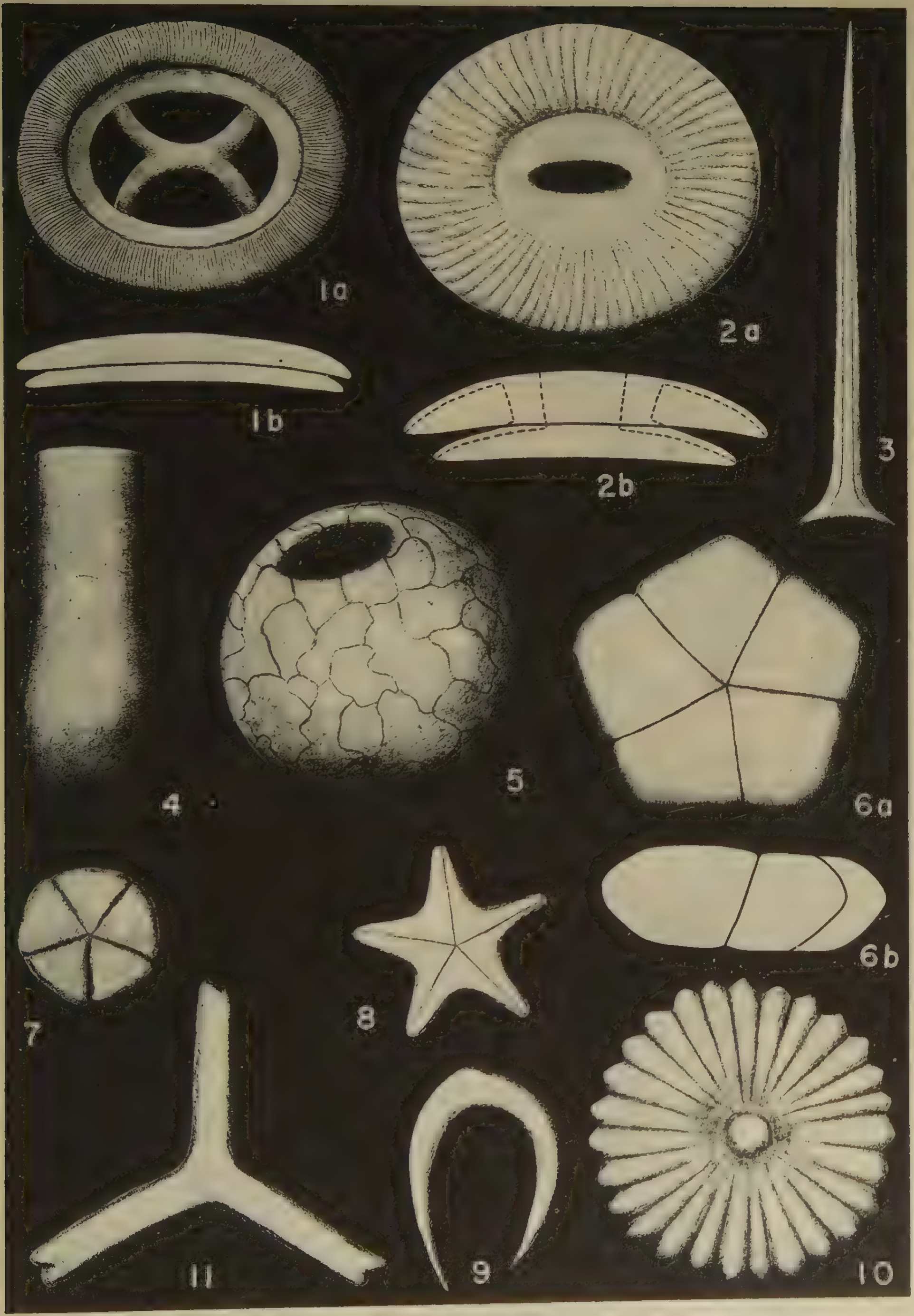
7—*Braarudosphaera discula*, n. sp., holotype. (p. 394)

8—*Micrantholithus* cf. *M. vesper* Deflandre, same locality as for fig. *6*. (p. 394)

9—*Ceratolithus* cf. *C. cristatus* Kamptner, Recent Pacific sediment at Lat. 04°35.3′N, Long. 139°57.7′W. (p. 394)

10—*Discoaster multiradiatus*, n. sp., holotype. (p. 396)

11—*Discoaster tribrachiatus*, n. sp., holotype (p. 397)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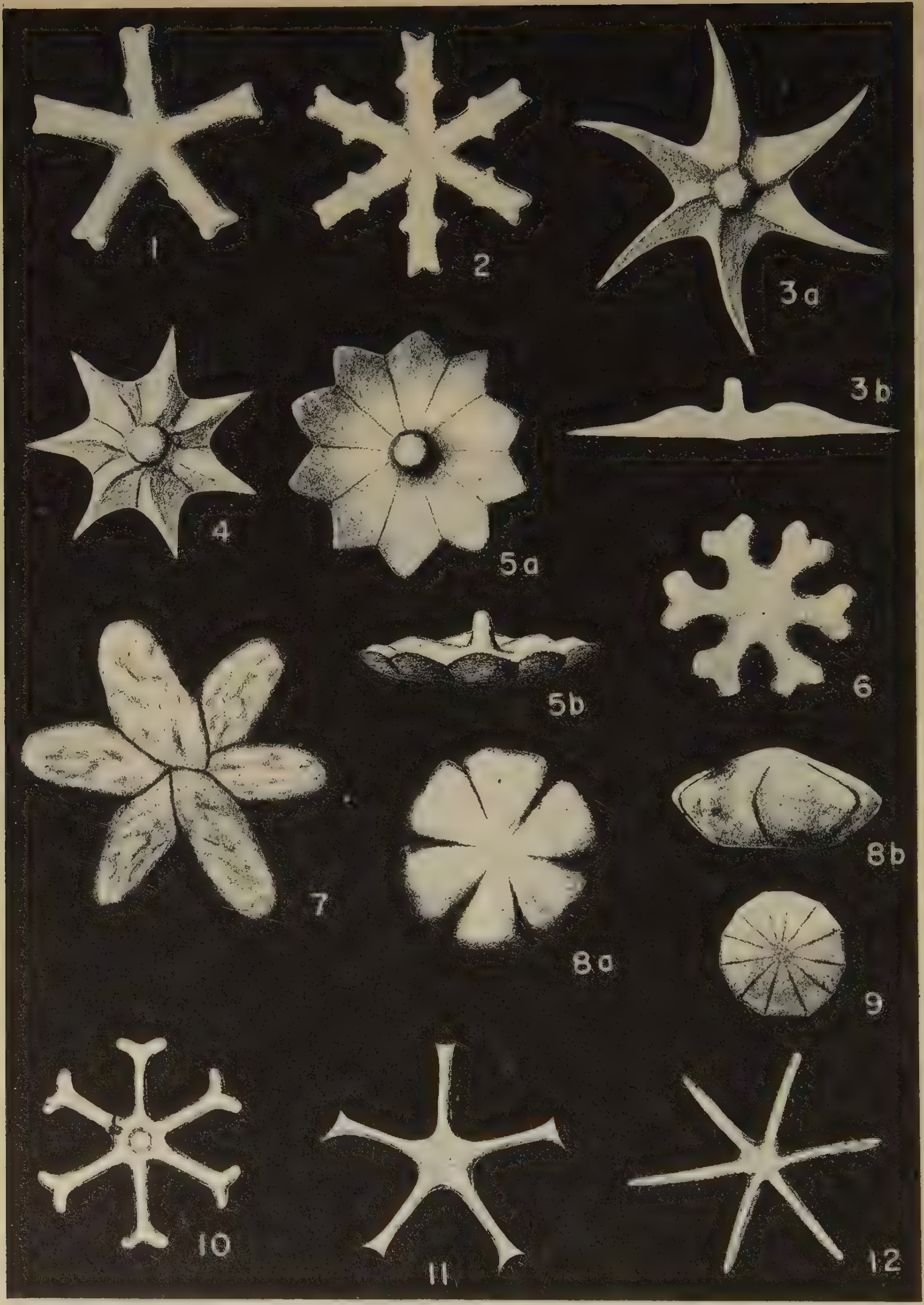
Bramlette and Riedel, Discoasters and related microfossils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Bramlette and Riedel, Discoasters and related microfossils

Recent *Rhabdosphaera claviger* Murray and Blackman. Lopadoliths, of which one of the various forms is figured on pl. 38, fig. 4, have been noted in many late Tertiary sediments, but have not been observed in rocks older than late Oligocene.

The soft parts of most of the following "form genera," which Deflandre places in his order Ortholithae, are quite unknown, and the skeletal remains of the various genera have practically nothing in common, apart from the individual parts having the optical properties of unit crystals. For these reasons, it seems premature to group them into a taxonomic order, and desirable to regard them for the present, as genera incertae sedes. Later investigations may reveal other forms (perhaps intermediate between known "genera") providing a sounder basis for a classification.

Genus THORACOSPHAERA Kamptner
Plate 38, figure 5

Small, spherical tests assigned to this genus are found very commonly in Tertiary strata. Although the tests have been found in Recent sediments, the living organism has not been described.

The spherical tests often have a "buccal opening." Deflandre's investigations led him to the conclusion that the presence or absence of such an opening is not an important taxonomic character, and our observations tend to confirm this view. The classification of members of this genus should probably be based in part on the nature of the individual plates forming the test. The plates of all of the specimens which we have observed are irregular in shape (pl. 38, fig. 5) and imperforate, in contrast to the polygonal, perforate plates of the figured specimen of *Thoracosphaera heimi* (Kamptner, 1927, fig. 6). Thus our form resembles *T. imperforata* Kamptner (1946) in the imperforate plates but not in the shape of the plates.

No discrimination of species has been attempted here, and the genus seems to extend from the Recent back to the Cretaceous.

Genera BRAARUDOSPHAERA Deflandre and MICRANTHOLITHUS Deflandre
Plate 38, figure 7, 8

These two genera of Deflandre (1947, 1950) comprise his family Braarudosphaeridae ("shell consisting of pentaliths, elements consisting of five pieces of crystalline calcite with characteristic orientation"). The typical test of *Braarudosphaera* has the form of a regular dodecahedron, composed of 12 pentaliths. *Braarudosphaera* contains two previously described species, *B. bigelowi* (Gran and Braarud) and *B. deflandrei* Lecal, distinguished on the orientation of the segments of the pentalith, and *Micrantholithus* contains two species (*M. flos* Deflandre and *M. vesper* Deflandre) which are differentiated apparently on the general form of the segments of the pentalith. *Micrantholithus* might better be considered merely as a subgenus of *Braarudosphaera*.

BRAARUDOSPHAERA BIGELOWI (Gran and Braarud) Deflandre
Plate 38, figures 6a, b

The isolated pentaliths characteristic of this species have been observed throughout

EXPLANATION OF PLATE 39

All illustrations ×2500.

FIGS. *1—Discoaster tani*, n. sp., holotype. (p. 397)
2—Discoaster tani nodifer, n. subsp., holotype. (p. 397)
3a, b—Discoaster lodoensis, n. sp. *3a*, vertical view of holotype; *3b*, sketch of lateral view. (p. 398)
4—Discoaster saipanensis, n. sp., holotype. (p. 398)
5a, b—Discoaster barbadiensis Tan, sens. emend. *5a*, vertical view of pleisotype; *5b*, slightly oblique lateral view. (p. 398)
6—Discoaster deflandrei, n. sp., holotype. (p. 399)
7—Discoaster aster, n. sp., holotype. (p. 400)
8a, b—Discoaster woodringi, n. sp. *8a*, vertical view of holotype; *8b*, lateral view. (p. 400)
9—Discoaster perplexus, n. sp., holotype. (p. 400)
10—Discoaster challengeri, n. sp., holotype. (p. 401)
11—Discoaster pentaradiatus Tan, sens. emend., plesiotype. (p. 401)
12—*Discoaster brouweri* Tan, sens. emend., Miocene marl, road cut at US Agric. Field Station at Mafron, Hati. (p. 402)

the Tertiary and in Cretaceous strata. Deflandre reports it as occurring in Recent sediments but we have not yet observed it here. There would seem to be some question about the identity of the original *Pontosphaera bigelowi* Gran and Braarud (1935) and the forms figured by Deflandre under this specific name. The original figure of this species does not show the characteristic five segments forming the pentaliths.

BRAARUDOSPHAERA DISCULA Bramlette and Riedel, n. sp.
Plate 38, figure 7

Pentaliths nearly round, tending to be more or less pentagonal in shape, with the sutures between the five segments reaching the margin at or very near the angles of the pentagon. The individual segments of the pentaliths show crystallographic orientations resulting in a similar extinction order to *B. bigelowi,* between crossed nicols. Diameter usually 6–9 microns.

Type locality.—Universidad formation (middle or lower Eocene), Loma Principe, Ave. de los Presidentes, Havana, Cuba.

This species differs from *B. bigelowi* in the more rounded form of the pentaliths and position of the sutures. Its stratigraphic range has not been established, but it seems to be common only in the Eocene and particularly in the lower-middle Eocene.[1]

MICRANTHOLITHUS cf. M. VESPER Deflandre
Plate 38, figure 8

This form has been observed only in the Capay stage (lower Eocene) of the Lodo formation of California and in the basal part of the Plaisance limestone (middle or lower Eocene) of Haiti. *M. vesper* was originally described from the lower Lutetian of Donzacq (Landes), France.

Genus CERATOLITHUS Kamptner
Plate 38, figure 9

In this genus (or manipule of Deflandre) are placed small calcareous bodies shaped like horse-shoes with pointed ends, which are very common in Recent sediments and evidently occur, though sporadically, as far back as the Miocene. Judging from their widespread distribution in Recent deep-sea sediments, it appears that they are the remains of planktonic organisms which flourish in the warmer seas. The forms which we have observed all resemble *C. cristatus* Kamptner, and it is doubtful that specific distinctions can be made.

Genus DISCOASTER Tan

This "form genus" name is assigned to all discoasters—small, calcareous, stellate or rosette-shaped plates, derived from some planktonic organisms presumably related to the coccolithophores.

Tan Sin Hok has been the only worker seriously to attempt taxonomic work within this group, and his classification has in general been used by later workers (Deflandre, Colom, etc.) though not followed here. He divided the discoasters into three "genera" within a family Discoasteridae.

1. *Heliodiscoaster:* Rosette-shaped forms, with the arms (sectors) not separated from one another; they completely fill the disc.
2. *Eudiscoaster:* Star-shaped forms, all of the arms of which are distinct from one another at the center of the disc, at least on one surface. Number of arms varies from five to eight.
3. *Hemidiscoaster:* Star-shaped forms in which groups of arms are united to one another. The arms usually joined at angles of 120° in two groups of three each.

Within each of these "genera," species were distinguished on the basis of the number of rays and the presence or absence of a central knob. Varieties were distinguished on the basis of the width of the arms and the nature of the terminations.

The distinction of a genus *Hemidiscoaster* based on the type of union of the arms (as two triradiate forms superposed at the center of the asterolith) appears to us to be inapplicable. In an assemblage of six-rayed forms, one occasionally finds individual specimens showing the "*Hemidiscoaster*" character (two groups of three rays united at 120°) while otherwise identical specimens from the same locality show no such grouping of the arms. Also, it seems that the distinction of genera (*Heliodiscoaster* from *Eudiscoaster*) on the basis of the number of arms is not possible. Several distinctive forms of *Discoaster*, particularly from the lower Tertiary, have 8–13 arms, and can therefore not be placed in one or another of Tan's genera. We shall therefore consider all of the discoasters as belonging to the genus *Discoaster*. This genus can be attributed to Tan Sin Hok (1927), because although formally defining his three separate genera, he used these generic names in the sense of sub-genera; he refers, for example, to "*Discoaster Barbadiensis* nov. spec." and "*Discoaster Hilli* nov. spec.," which he places in the genera *Heliodiscoaster* and *Eudiscoaster*, respectively.

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[1] Note: After submitting manuscript, Deflandre called our attention to a rather similar form recently described as *Pemma rotundum* by B. Klumpp in Paleontographica, Bd. 3, abt. A, Stuttgart, Sept. 1953. We believe this form should also have been referred to the genus *Braarudosphaera,* but it appears to be a different species in having, on each segment of the pentalith, a central "Knopf mit einer feinen Durchbohrung."

Definition of the species of *Discoaster* presents many problems. Tan distinguished species primarily on the number of rays, which is apparently a useful taxonomic character, although most species exhibit considerable ranges of variation in this respect. Species with 10–15 rays often show a range of variation of two or three on either side of the mean, species with usually six rays have not been observed to vary beyond the limits of five to seven, and a three-rayed form seems never to deviate from this number. Some six-rayed forms (such as *D. deflandrei*) occasionally show rare, abnormal variations with as many as eight rays, and others (e.g., *D. challengeri*) vary abnormally to three rays, but these are regarded as teratological cases which need not be considered taxonomically. In spite of the fact that the number of rays is an important taxonomic character, the exact number cannot be given the importance indicated by Tan in his definition of species of *Eudiscoaster*, where all of the eight or nine-rayed forms were grouped into one species, the six-rayed forms into another, and the five-rayed forms into the third species.

The nature of the terminations of the arms, used by Tan for the differentiation of infraspecific groups (as in his varieties of *D. brouweri* and *D. molengraaffi*), is considered in the present paper as one of the more important characters of specific rank. The terminations of the arms of the discoasters may be undifferentiated (rounded or abruptly truncate, as in *D. brouweri* s.s. or *D. perplexus*), sharply pointed (e.g., *D. lodoensis*) or bifurcate. The nature of the terminal notching or bifurcation of the arms seems a relatively constant and important character: in *D. pentaradiatus* the two terminations are pointed in such a manner that there is little difficulty in distinguishing six-rayed examples of this species from *D. challengeri* in which the terminations are rounded, and in *D. deflandrei* the outlines of the terminal bifurcations tend to have a peculiar subangular character which is quite different from the rounded terminations of thick-rayed examples of *D. challengeri*. Some forms (particularly in late Tertiary sediments) are observed having one branch of the bifurcation much more strongly developed than the other (text fig. 2), a character which appears to a certain extent in *D. pentaradiatus*. Apart from the cases of simple bifurcation, forms have been observed which have three prongs at the end of each arm: these forms have not been considered in this paper, although this characteristic branching may later prove to be of taxonomic value.

In a few forms, the arms bear lateral projections which are at least sufficiently constant to be considered as of some taxonomic value (as in our *D. tani nodifer* and perhaps in the undescribed *D. mirus* of Deflandre, 1952b, p. 465, fig. 362 Z). Width of the arms, which is often related in a general way to the overall robustness of the whole asterolith, is an important taxonomic feature, although it varies within moderately wide limits for each species. Two factors which may cause some of the variation of this character within a species are the amount of calcium carbonate available to the organism in its marine environment, and the stage of development of the organism (an immature asterolith may tend to have thinner arms than an older example). The effects of these factors are impossible to evaluate at present, especially as we have practically no information on the type of organism which produces the asteroliths. Despite these uncertainties, it is possible to define the width of the rays of each species within reasonable limits, and in some cases to use this character to assist in the distinction of species: for example, *Discoaster pentaradiatus* has thinner arms than *D. challengeri*, which it resembles in many other respects. It may be mentioned that there is a tendency for the rays of some of these six-rayed forms to become progressively thinner from the early to the late Tertiary, but the significance of this must remain a matter of speculation.

The structure of the central area of discoasters is often difficult to determine, because the asterolith has to be examined in side view, and some of the characters are so small as to be near the limit of resolution of an ordinary microscope. The most common modification of the central area is its growing outward to form a type of knob or stalk, which may be quite prominent, as in *Discoaster barbadiensis*, or small and inconspicuous as in some examples of *D. challengeri*. Sometimes the stalk appears stellate in vertical view; many specimens of *D. tani*, for example, show a central star, the points of which alternate with the arms. Although the presence or absence of a central knob or stalk is sufficiently constant to be used as a diagnostic feature of some species (as *D. barbadiensis*), there are other species (e.g., *D. multiradiatus*) of which some specimens in a given assemblage have a small knob, while in others it is not apparent. This may be the result of dimorphism of the asteroliths on individual organisms, of which there are many examples in the typical coccolithophores.

Finally, there are many discoasters in which the arms are not in a single plane, but curved like the ribs of an umbrella (text fig. 3b). This bending of the arms is a rather constant feature in species such as *D. tani*, *D. brouweri*, and some others. Deflandre (1952b, p. 476, 468) has pointed out that this may indicate that the discoasters covered the outer surface of a spherical organism, as do coccoliths.

DISCOASTER MULTIRADIATUS Bramlette and Riedel, n. sp.

Plate 38, figure 10

Asterolith rosette-shaped, consisting of usually 16–24 rays joined throughout their length though depressed along the sutures and bluntly pointed distally to produce a serrate margin. Central area of both faces often shallowly depressed, with usually a very small knob or stem in the center. Total diameter usually 9–15 microns.

This species differs from *D. barbadiensis* in the greater number of rays, and in being more nearly complanate and thinner in proportion to the diameter. It differs from *D. perplexus* in the greater diameter and serrate margin.

Type locality.—Velasco shale (Paleocene or uppermost Cretaceous), 500 meters N 70° W of Estacion Velasco, approximately 75 km. W of Tampico, Mexico.

Other occurrences.—Lodo formation (Paleocene, Zone D of Laiming, 1940, p. 551), Lodo Gulch, Fresno County, California; Lizard Springs formation (Paleocene or uppermost Cretaceous) Lizard Springs, Trinidad; Waipawan Stage (Paleocene), Hawke Bay, North Island, New Zealand; Scripps Mid-Pacific Sample no. MP–33C (Paleocene of Hamilton, 1953, p. 207), central Pacific.

Discussion.—This species seems to be restricted to the Paleocene, though some of the occurrences may prove to be of uppermost Cretaceous age.

Tan Sin Hok (1927, p. 118, fig. 2) figured a form resembling *D. multiradiatus* under the name *Discoaster ehrenbergi*, a species which he characterized merely as having 11 to 21 arms, without "kern." We have been unable to find such a specimen on re-examination of Tan's original samples, and moreover he figures two different forms under this name without giving any indication of where the specimens were found. Our species differs from that figured by Tan in the definite differentiation of the central area.

Besides varying considerably in total diameter, the number of rays, and the nature of the central area, as indicated in the above description, examples of *D. multiradiatus* vary in thickness. For example, specimens from Scripps Mid-Pacific Sample No. 33C are generally thicker than those from the type locality and other occurrences.

Some coccoliths superficially resemble *D. multiradiatus*, especially if somewhat corroded, but they are generally smaller and more delicate. In any questionable case, the structure as reflected by optical characters is quite diagnostic (p. 391).

DISCOASTER TRIBRACHIATUS Bramlette and Riedel, n. sp.
Plate 38, figure 11

Asterolith triradiate, consisting of three subcylindrical, commonly slightly tapering rays which are bluntly truncate and with or without a small terminal notch. Rays generally bent like those of *D. tani* and *D. brouweri*. Total diameter usually 8–13 microns (the type specimen is unusually large).

Tan Sin Hok (1927, p. 121) has named, but quite inadequately described, a *D. triradiatus* with two varieties. Examination of topotype material shows, however, that these are abnormal variations of other described species such as his *D. brouweri* and our *D. challengeri*; forms similar to *D. tribrachiatus* are not found in the material from Rotti.

Type locality.—Lodo formation (Capay stage, lower Eocene, Zone C of Laiming, 1940, p. 550), 314 ft. above base of Lodo formation, Lodo Gulch, Fresno County, California.

Other occurrences.—Lower part of Plaisance limestone (middle or possibly lower Eocene), 8 miles NW of San Michel, Haiti; Ramdat formation (lower Eocene), San Fernando area, Trinidad.

Discussion.—This characteristic species has been found at only a few localities, but these seem to be of approximately the same age, near the boundary between the lower and middle Eocene.

D. tribrachiatus is evidently not an abnormal triradiate development of any of the species with 6 rays. It somewhat resembles the six-rayed *D. tani*, but is an earlier form and is not found associated with the latter species.

DISCOASTER TANI Bramlette and Riedel, n. sp.
Plate 39, figure 1

Asterolith with five rays, but in some localities dominantly six. Rays rather heavy and of almost uniform width, abruptly truncate. The squared-off end of the ray commonly has a small notch, which in specimens from some localities is inconspicuous or absent. Small nodes are occasionally present on the sides of some rays, but these are seldom paired and not consistently developed on each ray as in the subspecies *nodifer*. The rays are generally bent like the ribs of an umbrella. Total diameter usually 9–15 microns.

This species differs from *D. brouweri* in the relatively heavy and stubby rays, the sporadic occurrence of lateral nodes, and commonly in the presence of a slight terminal notch on the rays.

Type locality.—Densinyama formation (upper Eocene), E side of Talofofo Road, S 80°E 1600 ft. from junction of Talofofo Road and Ridge Road, N Saipan.

Other occurrences.—Hospital Hill marl of the San Fernando group (upper Eocene), Hospital Hill, Trinidad; Waiarekan formation (upper Eocene), Cormack's Siding, W of Oamaru, New Zealand; Oceanic formation (upper Eocene), Bath, Barbados; Gatuncillo formation (upper Eocene), 2.7 miles NW of Rio Quebrancha Bridge, Panama Canal Zone; Ledian blue marl (upper Eocene), Cote des Basques, Biarritz, France.

Discussion.—This widespread species is common in the upper Eocene, but some evidence suggests that it may occur also in middle Eocene and lower Oligocene sediments. A central knob is apparent in some specimens, and this occasionally shows a peculiar star shape in vertical view.

D. TANI NODIFER Bramlette and Riedel, n. subsp.
Plate 39, figure 2

Asterolith differing from the typical form in the presence of distinct paired nodes on each ray, and usually in slight enlargement of the ends of the rays and more conspicuous terminal notches. It appears generally to have less bent arms than the typical form. Total diameter usually 13–18 microns.

Type locality.—Jackson formation (upper Eocene), 3½ miles SE of Isney, on the road to Silas, Alabama.

Other occurrences.—Waiarekan formation (upper Eocene), Cormack's Siding, W of Oamaru, New Zealand; Hagman formation (upper Eocene), Saipan, Marianas Islands.

Discussion.—The limited data suggest that this subspecies is more definitely restricted to the upper Eocene than is *D. tani* s.s. This subspecies never constitutes such a conspicuous element of the assemblage as does the typical form. It seems desirable to differentiate this subspecies because it does not occur with abundant *D. tani* in many localities, and it seems to be the only form of this species in a few other localities; also, it appears to be more restricted in range.

DISCOASTER LODOENSIS Bramlette and Riedel, n.sp.

Plate 39, figures 3a, b

Asterolith stellate, consisting of usually six (occasionally five or, rarely, seven) rays which are joined in their proximal half or one-third. Free, distal portions of the rays tapering gradually to a sharp point, and curved, all in the same sense, in the plane of the body of the asterolith. Centrally, a stem or knob projects from one surface. On the same side of the asterolith as the stem, each ray is raised as a prominent ridge extending radially to one side of the median line: the other side of the asterolith is more nearly plane. Total diameter usually 14–24 microns.

This species differs from *D. saipanensis* in the longer, thinner, and more curved arms.

Type locality.—Lodo formation (Capay stage, lower Eocene, Zone C of Laiming, 1940, p. 550), 314 ft. above base of Lodo formation, Lodo Gulch, Fresno County, California.

Other occurrences.—Lower Lutetian, Donzacq (Landes), France; lower part of Plaisance limestone (middle or possibly lower Eocene), 8 miles NW of San Michel, Haiti; Ramdat formation (lower Eocene), San Fernando area, Trinidad; Toledo member of Universidad formation (lower or middle Eocene), Cantera San Francisco, Puentes Grandes, Habana Province, Cuba.

Discussion.—This species may prove to be rather narrowly restricted to the upper part of the lower Eocene and the lower part of the middle Eocene. Specimens from some of the localities mentioned, particularly from Donzacq, have somewhat wider, straighter rays than those from the type locality, thus somewhat approaching *D. saipanensis.*

DISCOASTER SAIPANENSIS Bramlette and Riedel, n.sp.

Plate 39, figure 4

Asterolith stellate, with usually six or seven (rarely five or eight) straight rays which are joined for approximately half their length and taper distally to sharp points. Centrally, a stem or knob projects from one surface. Each ray has a prominently raised ridge extending radially to one side of the median line. Total diameter usually 9–13 microns.

Though this species shows similarities to both *D. barbadiensis* and *D. lodoensis*, the relationships were not sufficiently clear to assign it as a subspecies to either. It differs from *D. barbadiensis* in the more-separated and more sharply pointed rays, and the smaller number of rays. The differences from *D. lodoensis* have been pointed out in the discussion of that species.

Type locality.—Densinyama formation (upper Eocene), E side of Talofofo Road, S 80°E 1600 ft. from junction of Talofofo Road and Ridge Road, N. Saipan.

Other occurrences.—This species is very common in upper Ecoene samples from widely scattered localities.

DISCOASTER BARBADIENSIS Tan sens. emend.

Plate 39, figures 5a, b

"Krystaldrusen," EHRENBERG, Mikrogeologie, pl. 24, fig. A 67, pl. 25, figs. B 13 and 15, Leipzig, 1854.

"Crystalloids," JUKES-BROWNE and HARRISON, Quart. Jour. Geol. Soc., vol. 48, p. 178, figs. 4–6, 1892.

Discoaster barbadiensis TAN SIN HOK (in part), Jaarb. van het Mijnwezen in Ned. Oost-Indië, 1926, p. 119, 1927.

Heliodiscoaster barbadiensis Tan. DEFLANDRE, Bull. Soc. Francaise Microscopie, vol. 3, no. 2, p. 64, figs. 22 and 23, 1934.

Hemidiscoaster barbadiensis (Tan). COLOM and GAMUNDI, Estudios Geologicos, Madrid, no. 14, pl. 25, 1951.

Asterolith mushroom shaped, with a concavo-convex disc consisting of usually 9–13 rays, bearing a prominent stem on its concave surface. Rays joined throughout their length, with rounded or bluntly-pointed tips forming a serrate margin to the disc. Stem approximately conical, rounded distally. Total diameter usually 9–17 microns.

This species differs conspicuously from *D. multiradiatus* in the constant presence of a stem and fewer rays, and is equally distinct from *D. lodoensis* in the character of the rays, even though the latter has a stem.

Plesiotype locality.—Near middle of Oceanic formation (upper Eocene) at Bath, Barbados.

Other occurrences.—This species occurs in almost every Eocene assemblage examined, comprising nearly 100 samples from such widely scattered regions as California, Saipan, New Zealand, several Caribbean islands, France, Tunisia, etc.

Discussion.—Discoasters conforming to the emended description appear to be restricted to the Eocene and Paleocene (small and rare in the latter). The considerable range of variation of this species in different parts of the Eocene may make it desirable to differentiate some subspecies. For example, the small forms occurring very low in the Eocene should perhaps be distinguished taxonomically from the later forms, not only on account of their size, but also because of their relatively robust stem.

Tan Sin Hok's description of this species, "with 11 to 21 arms (sectors), which completely fill in the disc. In the centre, the arms are extended axially to form a 'kern.' Total diameter 15 microns, and smaller," was apparently based on the figures of Ehrenberg (1854) and Jukes-Browne and Harrison (1892), and perhaps on some specimens which he found in the sediments at Rotti, near Timor. We were unable to find specimens resembling *D. barbadiensis* on reexamination of portions of Tan's original samples, although a single specimen which conformed to his *D. barbadiensis* var. *bebalaini* was found. This small "variety" would not seem to be closely related to *D. barbadiensis*, principally because of the lack of a prominent stem.

The figures of Jukes-Browne and Harrison do not show the pronounced concavity on the side of the asterolith which bears the stem, and while this may be the case in some specimens, it is found that the shape is generally as shown in our figures. Assignment of our specimens to Tan's species seems justified because examination of many individuals from many samples of the Oceanic formation of Barbados indicates that the original figure of the side view was poor or of an abnormal specimen.

Reworking into later sediments of this abundant and ubiquitous form is evidently common, and seems to account for the reported occurrences in the Haitian Oligocene (Deflandre) and the Aquitanian-Burdigalian of Majorca, Spain (Colom and Gamundi) (see p. 390).

DISCOASTER DEFLANDREI Bramlette and Riedel, n.sp.

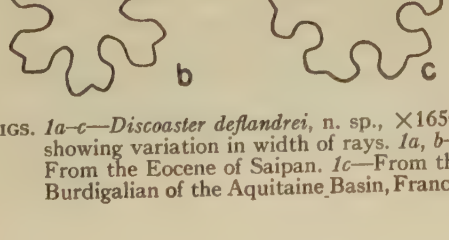
Plate 39, figure 6; text figures 1 a, b, c

Asterolith consisting of a central disc with usually six (rarely five or seven) broad, bifurcate rays which are generally as long as, or a little longer than, the radius of the central disc. Outline of the enlarged, bifurcating parts of the rays rounded or slightly angular; terminal notches angular rather than rounded. Spaces between the rays (proximally) subcircular, not angular, approximately as broad as the narrowest part of the rays and half as broad as the widest part of the rays. Total diameter usually 10–17 microns.

This species differs from *D. challengeri* in the large central disc and relatively broad rays, with the sides of the rays not parallel; and from *D. woodringi* in the bifurcate rays with rounded spaces between them.

Type locality.—Cipero formation, Renz sample no. 90, type locality for the fauna of Zone I (lower Oligocene of Renz and of Cushman and Stainforth, 1945, p. 4), sea cliffs south of San Fernando, 375 ft. S of 35½ mile-post on railway, Trinidad.

Other occurrences.—Burdigalian (lower Miocene), Saint-Etienne d'Orthe, Aquitaine Basin, France; "Adelina marl" (lower Oligocene of Palmer and Bermudez, 1936, p. 227), Finca Adelina, E of Colon, Matanzas Province, Cuba; Densinyama formation (upper Eocene), Talofofo Road, N Saipan, Marianas Islands; Monterey formation (lower Miocene), Bradley Quadrangle, Salinas Valley, California; Culebra formation (upper Oligocene-lower Miocene), E side of



FIGS. *1a–c—Discoaster deflandrei*, n. sp., ×1650, showing variation in width of rays. *1a, b*—From the Eocene of Saipan. *1c*—From the Burdigalian of the Aquitaine Basin, France.

Gaillard Cut near Empire Bridge, Panama Canal Zone, and many other localities.

Discussion.—This species apparently ranges from the middle Eocene to the lower Miocene, inclusive, but is abundant only in the Oligocene. The considerable range of variation, particularly in the width of the rays, may make it desirable eventually to recognize several subspecies or varieties (text figs. 1a, b, c).

DISCOASTER ASTER Bramlette and Riedel, n.sp.

Plate 39, figure 7

Discoaster stella (Ehrenberg). COLOM and GAMUNDI, Estudios Geologicos, Madrid, no. 14, pl. 25, fig. 6, 1951.

not *Discoaster stella* (Ehrenberg). DEFLANDRE, Traité de Zoologie, vol. 1, fasc. 1, p. 465, figs. Y–Y″, 1952.

Asterolith stellate, with commonly five or six, rarely seven thick and wide rays which vary markedly in width and degree of separation, and terminate in a rounded or bluntly pointed tip. The rays are somewhat irregular in outline due to their rather rugose surface. Total diameter usually 8–20 microns.

Type locality.—Near top of Oceanic formation (lower Oligocene) at Bath, Barbados.

Discussion.—This rather nondescript and very variable species may actually include several unrelated forms, and the variability makes it difficult to separate the extremes from the usually much thinner-rayed *D. brouweri* on the one hand and *D. woodringi* on the other. Also, it varies greatly in size, including a very small form in the earliest Tertiary which is otherwise indistinguishable from the later, larger forms.

Colom and Deflandre have both applied Ehrenberg's name "stella" to somewhat similar discoasters, but *Actiniscus stella* Ehrenberg is a name which should properly be applied to a siliceous microfossil. It appears that Ehrenberg generally distinguished sharply between siliceous and calcareous fossils. There is some possibility that he also used the name *Actiniscus stella* for calcareous skeletal remains (e.g., Ehrenberg, 1854, pl. 20, fig. 47) although the original reference was evidently to a siliceous microfossil.

D. aster is widely distributed geographically, and occurs throughout the Tertiary, and possibly in the Quaternary in which occur rare specimens of rather similar form.

DISCOASTER WOODRINGI Bramlette and Riedel, n.sp.

Plate 39, figures 8a, b

Discoaster brouweri var. *delta* Tan Sin Hok. DEFLANDRE, Bull. Soc. Francaise Microscopie, vol. 3, no. 2, text-figs. 20, 21, 24 (not 25), 1934.

Asterolith discoidal, robust, consisting of usually six (rarely five) thick, almost triangular rays. The thickness of the asterolith is approximately half the diameter. Rays joined throughout their length, except where separated by rounding of distal margins, and bounded by prominent sutures extending to the center. Total diameter usually 11–14 microns.

This species differs from *D. aster* in the greater width, and less separation and blunter termination of the rays, though many forms in some samples appear to be intermediate between the two.

Type locality.—Marl from Locality 0–1 of Hadley (1934) (lower part of Oligocene), 50 meters SW of gate to Naval Academy, Mariel, Cuba.

Other occurrences.—Chalky marl (Oligocene), sea cliff along highway, ½ mile SE of plaza in Jeremie, Haiti; Densinyama formation (upper Eocene), Talofofo Road, N. Saipan, Marianas Islands; top of Oceanic formation (lower Oligocene) at Bath, Barbados; Zone II of Cipero formation (upper Oligocene), Retrench Quarry, Princes Town area, Trinidad; and in many other widely scattered localities, mainly Oligocene in age.

DISCOASTER PERPLEXUS Bramlette and Riedel, n.sp.

Plate 39, figure 9

Asterolith small, thin, discoidal, with circular outline modified only by the straight distal margins of the rays. Rays usually 11 or 12, occasionally 10 or 13, very elongated triangular, joined throughout their length and marked by sutures which are rather inconspicuous except under the phase-contrast microscope. Total diameter generally 6–10 microns.

This species differs from *D. multiradiatus* in smaller size, flat surface of the rays and therefore less obvious sutures, and lack of serrate margin. In its size and general form, it more closely resembles some coccoliths.

Type locality.—Cipero formation (Zone II, upper Oligocene, Renz sample no. 555), Retrench Quarry, Trinidad.

Discussion.—This small, rather nondescript form was overlooked during most of this investigation, and was not distinguished from the numerous forms of coccoliths. However, it obviously does not belong with the coccoliths because it shows the optical properties of a single calcite crystal, as do all the discoasters. It was observed in a few other samples of middle Tertiary age, but was not recorded.

DISCOASTER CHALLENGERI Bramlette and Riedel, n.sp.

Plate 39, figure 10

Discoaster molengraaffi var. γ TAN SIN HOK, Jaarb. van het Mijnwezen in Ned. Oost-Indië, 1926, p. 121, text-fig. 2 (11), 1927.

Discoaster. TAN SIN HOK, ibid., p. 111, text-fig. 1 (3).

Discoaster to upper right of center of figure. MURRAY and RENARD, Report on Deep-Sea Deposits, based on specimens collected during the voyage of H.M.S. *Challenger*, pl. 11, fig. 4, 1891.

Asterolith with usually six (occasionally five or rarely seven) rays which are subcylindrical, distally bifurcate into short, rounded terminations. Rays show little or no curvature of the type found in *D. brouweri.* Widening of rays in central area never pronounced; central area with or without a small, circular knob. Rays typically thin, but varying considerably in width. Total diameter generally 10–13 microns.

D. challengeri differs markedly from *D. deflandrei* in the thin rays of uniform width and generally more delicate structure. The distinction from *D. pentaradiatus* is discussed under that species.

Type locality.—Lengua formation (lower Miocene), E side of Lengua Settlement Road, about 60 yds. from junction with Realize Road, approximately three miles S of Princes Town, Trinidad.

Other occurrences.—Suva formation (Miocene), just north of hospital, Suva, Fiji; chalk (late Tertiary), Bebalain, Rotti, East Indies (Sample no. 168 of First Netherlands Timor Expedition); Bowden (?) formation (middle ? Miocene), Buff Bay, Jamaica; Tagpochau limestone (lower Miocene), Saipan, Marianas Islands; and many other widespread Miocene localities.

Discussion.—This species is abundant and of widespread occurrence in the Miocene, and also occurs in probable upper Oligocene (as in the upper part of the Cipero formation, Trinidad) where it is however generally represented by more robust forms which it may prove desirable to distinguish as a separate subspecies.

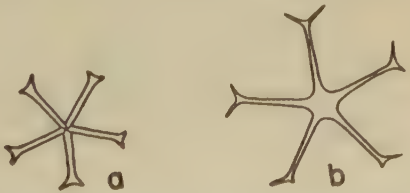
The upper limit of its occurrence is questionable, as virtually no Pliocene material is available. The assumption of its occurrence in the Recent, made first by Tan Sin Hok on the basis of its occurrence (with his type *D. molengraaffi*) in a *Challenger* sample (Murray and Renard, 1891) seems doubtful. Neither form has been recorded or observed by us in other purely Recent deposits, though they are present in surface samples where other evidence indicates reworking. The probability of its occurrence at *Challenger* Station 338 being due to reworking has been discussed above (p. 389).

DISCOASTER PENTARADIATUS Tan sens emend.

Plate 39, figure 11; text figures 2a, b

Discoaster pentaradiatus var. γ TAN SIN HOK, Jaarb. van het Mijnwezen in Ned. Oost-Indië, 1926, p. 120, text-fig. 2 (14), 1927.

Asterolith with five (though perhaps as commonly six) thin rays having bifurcations which are characteristically sharp and delicate. The distal margin of the ray between the bifurcation is a smooth curve, in contrast to the more angular notch of *D. challengeri* and *D. deflandrei.* On each ray, one branch of the bifurcation is commonly longer than the other. As in *D. challengeri,*



FIGS. *2a, b*—*Discoaster pentaradiatus* Tan Sin Hok, sens. emend., ×1650. *2a*—Specimen from Rotti, near Timor (after Tan Sin Hok, 1927). *2b*—Specimen from the Miocene of Haiti, showing long and unequal bifurcate points.

the rays normally show little of the type of bending characteristic of *D. brouweri*. Total diameter usually 9–12 microns.

Plesiotype locality.—Marl (Miocene), 1.6 miles S of Mafron, Haiti.

Discussion.—The central area of the asterolith is usually more enlarged than indicated in Tan's figure (figs. 2a, b). Tan indicates, without further discussion or figures, that this species has several varieties corresponding to those of his *D. brouweri*. Any such entirely different forms could hardly be included in *D. pentaradiatus*, for the reasons outlined in the discussion of *D. brouweri*.

Restriction of this species to five-rayed forms seems unjustified, and distinction from *D. challengeri* therefore becomes somewhat difficult in some occurrences, because the latter species can also have five rays. The character of the bifurcations and the delicate structure are considered more diagnostic features.

This species is widespread in Miocene strata, and has not been observed below the Miocene. The upper limit of its occurrence is not known, as almost no Pliocene discoaster assemblages are available, and it apparently does not occur in the Recent. Typical forms occur in the Lengua formation of Trinidad, Suva formation of Fiji, the Tagpochau limestone of Saipan, and at many other localities.

DISCOASTER BROUWERI Tan sens. emend.
Plate 39, figure 12; text figures 3a, b

Discoaster brouweri typ. TAN SIN HOK, Jaarb. van het Mijnwezen in Ned. Oost-Indië, 1926, p. 120, text-fig. 2 (8a, b), 1927.

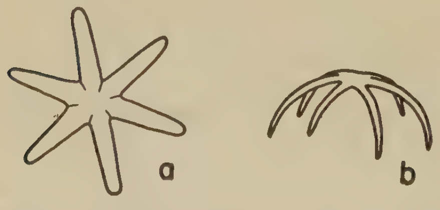
Discoaster molengraaffi typ. TAN SIN HOK, ibid., p. 120, text-fig. 1 (9), 1927.

?*Discoaster* aff. *D. brouweri* Tan. DEFLANDRE, Bull. Soc. Francaise Microscopie, vol. 3, no. 2, p. 66, text-figs. 15–19, 1934.

Tan Sin Hok (1927) described this species to include several very different six-rayed forms of his genus *Eudiscoaster*. Apart from the typical form, he recognized the four varieties α (club-shaped termination of rays), β (very broad rays, notched terminally), γ (rays less broad terminally, thickened and somewhat notched) and δ (broad rays not separated, but asterolith margin serrate by indentations at the sutures and by notching at the ends of the rays). Some of his varieties are so distinct in appearance and occurrence from the typical form that they are assigned to new species described here. We restrict his species to the typical form, which is the dominant form in his original samples (see his pl. 3, fig. 1). *D. molengraaffi typ.* Tan Sin Hok, which was based on a figure from a sample of the *Challenger* expedition (Murray and Renard, 1891, pl. 11, fig. 4) is considered to be identical with *D. brouweri*, sens. emend., as the generic distinction seems inapplicable (see discussion of *Hemidiscoaster*, p. 394).

The restricted species has usually six rays (occasionally five and rarely, if ever, seven) which are thin, elongate, bluntly pointed, not bifurcate; they are generally more tapering in Tan's samples than his figure indicates (see our text fig. 3a). The rays are more or less bent like the ribs of an umbrella, and this character can become extreme in certain occurrences (e.g., text fig. 3b, from the Miocene of Suva, Fiji). The examples in Tan's original material show less proximal enlargement of the rays to form a slightly expanded central area than do the usual forms which we include in this species. Perhaps some of the forms, for this reason, may later be separated as distinct subspecies.

This species is one of the most abundant and widespread forms of the late Tertiary, occurring in nearly every Miocene sample examined from both sides of the Atlantic, Mediterranean and Pacific Oceans. It also occurs, less abundantly in sediments of probable late Oligocene age, and extends up into the Pliocene.



FIGS. 3*a*, *b*—*Discoaster brouweri* Tan Sin Hok, sens. emend., ×1650. *3a*—Vertical view of a specimen from Rotti, near Timor. *3b*—Lateral view of a specimen from the Suva formation, Fiji.

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718

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The Riddle of Sterol and Carotenoid Metabolism in Muds of the Ocean Floor[1]

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INTRODUCTION

Although sterols are readily demonstrable in extracts of soil (9) and of fresh sedimentary material from marine shores or from saline sloughs, by the blue or green color responses of their chloroform solutions to the Liebermann-Burchard reagent, they have not been so detected in similar lipide extracts of sediment from the deep ocean floor (2).

Furthermore, xanthophyllic carotenoids, which greatly preponderate over members of the hydrocarbon or carotene class in green plants of land and sea, as well as in finely suspended marine detritus, have nevertheless been found to be in far lower concentrations than carotenes in ocean-bottom sediments (3, 5).

There is at present no indication as to whether either of these persistent observations may reflect chemical reduction by removal of hydroxyl groups, by saturation of double bonds, by both of these processes, or through more drastic degradation of the organic molecules in the anaerobic milieu of buried ocean muds. Little is apparently known regarding the biochemical origins of the pale, waxy, nonsaponifiable residues recovered from fat-solvent extracts of deep ocean muds, although Rosenfeld (7, 8) and others have demonstrated the reduction and decarboxylation of fatty acids by lipoclastic anaerobes. It has furthermore been shown by Clarke and Mazur (1) that the fatty acids of diatoms and of marine muds decrease in concentration on long standing (even under N_2), while alcohols and hydrocarbons increase.

Microorganisms are responsible for countless changes in marine organic matter (10) and are obvious suspects in questions concerning

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the anaerobic metabolism of sterols and carotenoids in ocean sediments. It was considered, however, that a logical beginning should involve a survey of possible effects of certain simple catabolites of marine anaerobic microflora, e.g., H_2, CO_2, and H_2S, at high hydrostatic pressures prevalent at great ocean depths. This report concerns some preliminary observations of that kind.

EXPERIMENTAL

Hydrostatic pressures were applied to the material within 10 × 75 mm. glass tubes, closed at each end with a neoprene stopper, and contained within sealed, thick-walled stainless steel cylinders (11).

In studies on cholesterol, 2 ml. of the chloroform solution (1 mg./ml.) was adsorbed upon a little finely powdered $CaCO_3$ within each tube; the solvent was then evaporated by gently warming in a current of illuminating gas. A thin film of glycerol was applied around the inside of the mouth to prevent creeping and escape of the cholesterol during evaporation of the chloroform.

Next, with both stoppers inserted, hydrogen gas was introduced for several minutes through a hypodermic needle entering through the glass-to-rubber junction, and escaped through a second needle similarly placed. Finally, 2 ml. of water was similarly introduced, and both needles were then withdrawn leaving the tube sealed. Hydrostatic pressures were then applied at 30°C. for 4 days, three samples receiving 530 atm., three 265 atm., and three 1 atm., while the control triplicates contained unpressurized H_2 but no $CaCO_3$. In the ultimate analyses, the $CaCO_3$ was dissolved in dilute acetic acid, and the entire contents were extracted with chloroform which was ultimately reduced to a volume of 10 ml. Two-milliliter aliquots, mixed with 4 ml. of Liebermann-Burchard reagent (acetic anhydride + concentrated H_2SO_4, 20:1) in a Klett colorimeter tube, were compared, after standing 30 min. in the dark, with a standard, using a green light filter.

RESULTS

Samples (in triplicate)	Klett colorimeter readings with green filter	
1. Nonadsorbed control (1 atm.)	102; 100; 96	Av. = 99.3
2. Adsorbed control (1 atm.)	100; 108; —	Av. = 104
3. Under 265 atm.	100; 104; 92	Av. = 98.7
4. Under 530 atm.	112; 101; —	Av. = 106

These results, disregarding minor errors in recovery and in colorimetry, indicate that the cholesterol remained unchanged as to the persistence of its double bond and its hydroxyl group. Although the duration was but 4 days, nevertheless the experimental temperature exceeded by nearly 30°C. that which prevails in the deep ocean, and would therefore have provided for an acceleration of some eight- or ninefold in any likely chemical reaction. Moreover, the available amount of H_2 exceeded by tenfold that theoretically required for reducing cholesterol to cholestane and water. It therefore seems unlikely that chemical reduction of cholesterol may occur merely through the agency of H_2 in the ocean floor at high hydrostatic pressures, e.g., at a depth as great as 3 miles.

Zeaxanthin was studied in the same apparatus, with the omission of solid $CaCO_3$. A volume of 4 ml. ethanolic zeaxanthin solution (3 μg./ml.) was introduced into each of 12 pressure tubes. Following evaporation of the solvent as in the preceding experiments, 0.2 ml. of ethanol and 2 ml. of distilled water were added. Hydrostatic pressure was applied in the presence of dissolved H_2, at 30°C. for 8 days; four tubes were held at 730 atm. and four at 1 atm., while the remaining four were exposed to CO_2 at 1 atm.

In analyzing, each sample was evaporated to dryness at 70°C. in a stream of illuminating gas, the carotenoid residue was dissolved in 10 ml. of ethanol, and its concentration was measured photoelectrically at 452 mμ with a Beckman instrument. The results were as follows:

Gas used (quadruplicate samples)	Pressure applied (8 days at 30°C.)	
	1 atm.	730 atm.
	Residual zeaxanthin μg./ml.	
H_2	1.12; 1.16; 1.28; 1.57. Av. = 1.28	1.12; 1.13; 1.18; 1.30. Av. = 1.18
CO_2	1.21; 1.35; 1.47; —. Av. = 1.34	

These data, yielding but insignificant variations between aliquots, suggest that neither H_2 under high hydrostatic pressures, nor CO_2 at 1 atm. decomposes zeaxanthin.

In additional experiments, the possible effects of CO_2 were explored further, as well as the potential influence of H_2S, which, like the other two gases used, also occurs in marine sediments. An attempt was also made to determine whether the presence of a representative deep-sea sediment might serve in a catalytic manner.

Ethanol (0.5 ml.) was added to the dry pigment residue in each tube, and 2 ml. of 5% marine mud suspension was then added in place of distilled water. (The marine mud was taken from about the 1-m. and the 2-m. levels of core sample XXIX:219, 7A, and 15A, collected at an ocean depth of 1500 m., and was sterilized, before use, in an autoclave at 121°C., 15 lb. pressure for 15 min.).

In the first series, paired samples were exposed to H_2, to CO_2, or to H_2S, at hydrostatic pressures of (*a*) 1 atm. and (*b*) 730 atm., for 7 days at 24°C. In the second set, quadruplicate samples were exposed to H_2

and twin samples to CO_2, at the above hydrostatic pressures for 8 days at 30°C.

Results are tabulated as follows:

			Pressure	
			1 atm.	730 atm.
Gas used	Time *days*	Temperature *°C.*	Residual zeaxanthin *µg. /ml.*	
H_2	7	24	1.12; 1.05. Av. = 1.08	1.13; 1.15. Av. = 1.14
H_2	8	30	1.15; 1.33; 1.41; 1.40. Av. = 1.32	1.55; 1.30; 0.71; 1.13. Av. = 1.17
CO_2	7	24	1.18; 1.05. Av. = 1.11	0.91; 0.93. Av. = 0.92
CO_2	8	30	1.05; 1.01. Av. = 1.03	0.41; 0.54. Av. = 0.47
H_2S	7	24	1.18; 1.11. Av. = 1.14	1.20; 1.14. Av. = 1.17

Pressurized samples from both H_2 and CO_2 systems yielded no epiphasic (hydrocarbon-like) but entirely hypophasic (xanthophyllic) pigments in 95% methanol; they were completely adsorbed from petroleum ether solution in two discrete bands upon a $CaCO_3$ column, thus indicating that no carotene-like compounds had been generated by chemical reduction of the dihydric alcohol zeaxanthin. Moreover, there were no recognizable differences between the chromatograms of the experimental solutions and those of the parent stock solutions similarly diluted.

Discussion

The extraneous cause is not known for the single aberrant low value in the third sample of the H_2-pressurized set of the last series. While H_2 and H_2S seemed to be generally ineffective, even under great hydrostatic pressures, there were manifest losses of zeaxanthin in certain of the CO_2-pressurized series. The zeaxanthin apparently remained intact when held in the presence of CO_2 at 1 atm. for 8 days at 30°C., without the addition of marine sediments, and even in the presence of this and CO_2 at 1 atm. of pressure for 7 days at 24°C. There were losses, however, in the concentrations of the carotenoid in the three other instances where CO_2 was used, i.e., amounting to 17.6% in the presence of sterile marine mud and CO_2 under 1 atm. of pressure for 8 days at 30°C.; 18.6% in the presence of sterile marine mud and CO_2 under hydrostatic pressure of 730 atm. for 7 days at 24°C.; and 62.4% in the presence of the sterile mud and CO_2 under hydrostatic pressure of 730 atm. for 8 days at 30°C.

There is no reason for believing that CO_2 per se might exert an oxidizing or otherwise destructive effect upon zeaxanthin. It is known, however, that carotenoids, especially xanthophylls, are labile in relatively acid media, especially where oxidizing agents are present.

While the CO_2 used was free of oxygen, there was, in the samples exposed to the sterile marine sediment in the presence of this gas, a tangible source of oxidation. The preliminary sterilization of a marine mud in an autoclave containing atmospheric oxygen would doubtless assure the existence of *ferric* compounds from the ubiquitous sedimentary iron oxides, hydroxides, or sulfides. Excess CO_2 in aqueous media provides an acidic condition, i.e., pH 3.7 at atmospheric pressure and somewhat more acidic values as the pressure of CO_2 is increased (6, 4). Such an acidic condition would undoubtedly provide a source of ferric ions, and these, whether directly or through a primary attack upon the small amount of ethanol present, should constitute an effective means for oxidative bleaching of the zeaxanthin. The presence of ferric ions would, on the other hand, be precluded by such reducing agents as H_2S or H_2 in excessive concentrations.

While such gases as H_2, H_2S, CO_2, and others (e.g., CH_4 and NH_3) may be detected in small quantities in natural anaerobic marine sediments, there would appear to be no likelihood that unsaturated organic compounds should undergo extensive changes as a result, even at high hydrostatic pressures, since CO_2, the only component theoretically capable of dissolving iron compounds, is present in but small quantities, is furthermore in an alkaline, reducing medium, and, in the absence of O_2, would encounter little or no iron in the ferric condition.

The results of these experiments suggest that such compounds as sterols and carotenoids are not chemically reduced through the direct action of dissolved gases in the anaerobic muds of the ocean floor. It will be necessary, therefore, to explore the question further with reference to possible biochemical roles played by endemic anaerobic microorganisms.

SUMMARY

Cholesterol and zeaxanthin remained unaltered by H_2 dissolved in neutral aqueous systems at high hydrostatic pressures. Zeaxanthin remained chemically unaltered by saturated aqueous CO_2 systems at a hydrostatic pressure of 1 atm., or by H_2 or H_2S in sterile marine sediment suspensions at high hydrostatic pressures. Some bleaching occurred in the presence of CO_2 and the sediment together, presumably through oxidation by ferric ions.

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Foraminifera and deep-sea research*

By Fred B. Phleger

INTRODUCTION

The Foraminifera have been of considerable value in study of certain problems of the deep sea. Sequences of planktonic species in deep-sea cores have been used to interpret stratigraphic sequences, for correlation, and to indicate possible marine conditions during glacial and interglacial times. These forms also have been used as indicators of marine water-masses, both in the modern ocean and in ancient seas. Benthonic species, used as tracers of sediment displaced from shallower into deeper water, have given considerable insight into deep-sea sedimentation. It is the purpose of this paper to summarize briefly our knowledge of the uses of Foraminifera in these and related problems, and generally attempt to evaluate the status of this phase of deep-sea research. There is no attempt to make this a complete discussion of the subject ; references are cited to illustrate the topics of discussion, and any omissions are not intended to imply criticisms of such work.

Foraminifera are marine Protozoa which may be either planktonic or benthonic in habitat, and live in all marine and semi-marine enviroments, from brackish marshes to the deep-sea. From an ecologic point of view they appear to constitute a dynamic series of populations which are constantly adapting themselves to marine environments. There is considerable morphologic variation giving rise to a large number of species and variants. The number of benthonic species is much greater than that of planktonic species, and this may be due in part to greater variation in the benthonic environments. The importance of Foraminifera in the study of marine sediment is that they produce a shell, or test, which becomes a part of the sediment when the animal dies or reproduces. The accumulation of these tests thus leaves a record in the sediment of the marine conditions in which these animals lived.

Accumulations of foraminiferal tests in deep-sea sediments are composed almost exclusively of planktonic species, with benthonic forms generally constituting only a small fraction of one percent of the total population. This planktonic population is dominated by *Globigerina*, *Globorotalia*, and their relatives, and in high concentration may be referred to as *Globigerina* Ooze. Planktonic species must be considered separately from benthonic types in any study of environment of deposition, since they represent different habitats and thus different environments. The following discussion is confined to planktonic Foraminifera except where indicated. The usefulness of Foraminifera in solving problems connected with the deep-sea is dependent upon a knowledge of their ecology, and much of the following discussion concerns what is known about modern distributions and methods of their study.

METHOD OF STUDY

Most studies of modern planktonic Foraminifera have been based on their occurrence

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in marine sediments, but some have been made on plankton tows. In taking plankton tows for this purpose it is advisable to use relatively fine-mesh bolting silk (nominal opening 0.203 or 0.158 mm), since the smaller forms may be lost in the coarser nets normally used for zooplankton tows. Samples should be preserved in formalin which is made basic by the addition of sodium carbonate, sodium borate, or hexamethylenetetramine. This is necessary to prevent solution of the tests of the planktonic Foraminifera, all of which are composed of calcium carbonate. The Clarke-Bumpus plankton-sampler (1950) has been used extensively to sample the plankton quantitatively at known depths, and the Nansen closing net also has been used. Recently, members of the Marine Foraminifera Laboratory have done extensive sampling of the upper 50-100 m. of water by vertical tows with a small, open-mouth net. None of these methods of collection gives a completely accurate quantitative picture of the distribution of planktonic Foraminifera in the water-masses where they live. Use of a fine-mesh net inhibits free flow of sea water through the sampler, so that the population obtained may be somewhat smaller than the actual population living in the water. Calculations of the amount of water strained under such circumstances may only be approximations. Actual measure of the amount of water strained with a meter wheel, as in the Clarke-Bumpus sampler, is only a relative measure because of the difficulty of calibration. In sampling deep layers the actual depth and pattern of towing is not known certainly ; depths are estimated by angle of the towing wire at the surface.

The modern assemblage of Foraminifera is accumulating in the surface sediment except where it is being destroyed by solution of calcium carbonate or where physical processes prevent accumulation. It is assumed that the fauna in a sediment lived in the water directly above and that the specimens sink immediately upon death or reproduction. Neither of these assumptions is strictly true, in all probability, but they appear to represent reasonable approximations.

It is desirable to obtain the actual surface of the sediment to sample properly the modern fauna. This can be done easily in deep water only by means of a small coring tube which may be handled vertically on shipboard so that the undisturbed sediment may be taken from the core. Such an instrument is described by PHLEGER (1951b) and several modifications of this gear are now in use. Other advantages of using the coring-tube principle in collecting such material is that a known area is sampled, and a measured thickness can be obtained. The samples thus lend themselves to quantitative studies. Snapper samples or mixed dredge samples in general are not reliable for making quantitative faunal studies of the modern population from sediments. Surface samples from long cores generally are mixed with deeper material due to the necessity of handling cores horizontally aboard ship.

DISTRIBUTION OF LIVING PLANKTONIC FORAMINIFERA

Real knowledge of the ecology of planktonic Foraminifera should be based, in large part, on understanding their distributions within the plankton. Only a few studies have been made of the distribution of living planktonic Foraminifera from plankton tows. Early work established that there are approximately 20 or 30 planktonic species based on their presence in plankton tows. More recently, quantitative studies have been made in the Atlantic by SCHOTT (1935), by PHLEGER (1945), and in the Gulf of Mexico by PHLEGER (1951b), and work is in progress on several hundred plankton tows which have been collected from the Pacific by J. S. BRADSHAW and others at the Scripps Institution of Oceanography. Studies which have been made are too few and incomplete to solve any problems of distribution of these forms, but some interesting generalizations may be made on the data which are available.

It appears that the largest populations of planktonic Foraminifera live in the upper layers of water. SCHOTT (1935) obtained several hundred specimens per tow from the upper 100 m. and many more, on the average, than he collected from greater depths. PHLEGER (1951b) found an average population of 5-6 per cubic meter of water in the upper 50 meters in the northwest Gulf of Mexico. At some stations, however, there were patches of higher concentration, up to 73 living specimens per cubic meter of water.

Live planktonic Foraminifra have been discovered at all depths which have been sampled. At a few stations larger live populations have been collected from depths greater than 100 m than from shallower layers of water. Living specimens also have been indentified from sediment samples collected with the short coring tube described above (PHLEGER, 1951b, p. 69 ; PARKER, 1954). These specimens either were living on the bottom or in the 15-20 cm of water directly above the bottom which is collected with this sampling device. These data certainly suggest that while planktonic Foraminifera appear to be most abundant in the upper water layers they do live throughout the water column all the way to the bottom. It is possible that they may live parts of their lives at different depths. The methods used at the Marine Foraminifera Laboratory in identifying live specimens employ the recognition of protoplasm in specimens which were preserved in formalin ; the biuret colour test for protein has been used by PHLEGER (1951b, p. 6), and PARKER (1954) has used the rose bengal stain described by WALTON (1952). It is possible that many of the forms collected from deeper layers were in a resting state and were not actively growing and reproducing at those depths. The abundance of young, thin-shelled specimens in all deep-water samples, however, suggests that some growth may occur in the deeper layers.

Most plankton samples seen by the writer contain empty tests of Foraminifera, as well as those having protoplasm. These may be somewhat more abundant at greater depths, but they also occur in abundance at some places in the shoal layers of water. This suggests that these forms do not sink immediately when the protoplasm disappears from the tests. It is unlikely that these empty tests had died or reproduced immediately before collection of the samples, otherwise the population would have survived for only a very short time. It is the opinion of the writer that these abundant empty tests are evidence that some mechanism is retarding sinking to the bottom. Turbulence in the seasonal water layer could be effective in preventing these tests from sinking for some time, especially during times of deep mixing caused by high wind. Deeper turbulence, while less effective, may also retard such deposition on the bottom.

The significance of these meagre data on distribution of planktonic Foraminifera in their natural habitat suggests that certain qualifications should be kept in mind in evaluating accumulations in marine sediment, as follows :

1. The fauna in a sediment may represent environmental conditions which existed throughout the entire water column, from the surface layer to the bottom. There may be several populations living in different depth environments, or the same population may be variously affected by environments at various depths. The

principal ecological effect, however, may be from the surface water layer. It may be possible to reconstruct conditions in the entire water column if we obtain sufficiently detailed understanding of the ecology of these organisms.

2. Planktonic Foraminifera do not sink immediately, depending upon water turbulence conditions, and may be deposited at some distance from where they actually lived. The distance of such transport cannot be established at the present time and must be variable.

DISTRIBUTION OF PLANKTONIC FORAMINIFERA IN SEDIMENT SAMPLES

Most of the information on the distribution of planktonic Foraminifera is based on their occurrence in sediment samples. Much of the early work on distributions was qualitative and was on sediment samples collected by methods whose reliability is questionable inasmuch as many pre-modern materials were obtained and the amount of sample used was variable. SCHOTT (1935) has given excellent quantitative data on the distribution of species in samples collected by the *Deutsche Atlantische Expedition* in low-latitude areas of the Atlantic. OVEY (in WISEMAN and OVEY, 1950, p. 59, table 1) has listed species characteristic of Arctic and Antarctic, temperate, and warm water based on quantitative study of nine samples from the Atlantic.

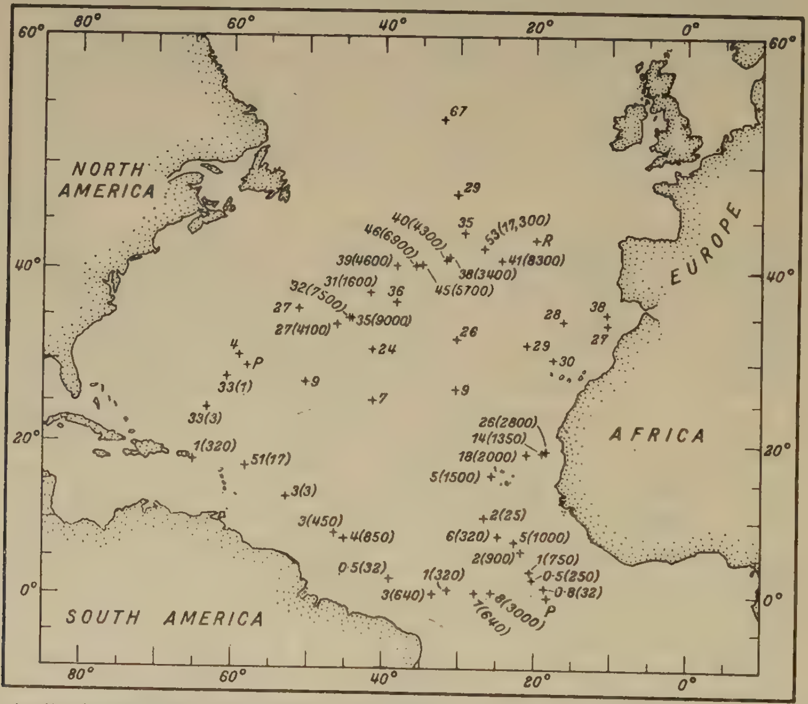

80°
60°
40°
20°
0°
60°
40°
20°
0°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
67
29
40(4300)
46(6900)
35
53(17,300)
R
41(8300)
39(4600)
38(3400)
45(5700)
31(1600)
36
32(7500)
27
35(9000)
27(4100)
26
28
38
27
29
30
24
4
P
33(1)
9
7
9
33(3)
26(2800)
14(1350)
18(2000)
5(1500)
1(320)
51(17)
3(3)
2(25)
3(450)
4(850)
6(320)
5(1000)
2(900)
1(750)
0·5(32)
1(320)
0·5(250)
0·8(32)
3(640)
8(3000)
7(640)
P

Fig. 1. Distribution of *Globigerina bulloides* d'Orbigny in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

More recently PHLEGER, PARKER and PEIRSON (1953) have listed generalized distributions in the North Atlantic based on the study of approximately 50 sediment samples in mid and low latitudes. The types of distributions listed by them are

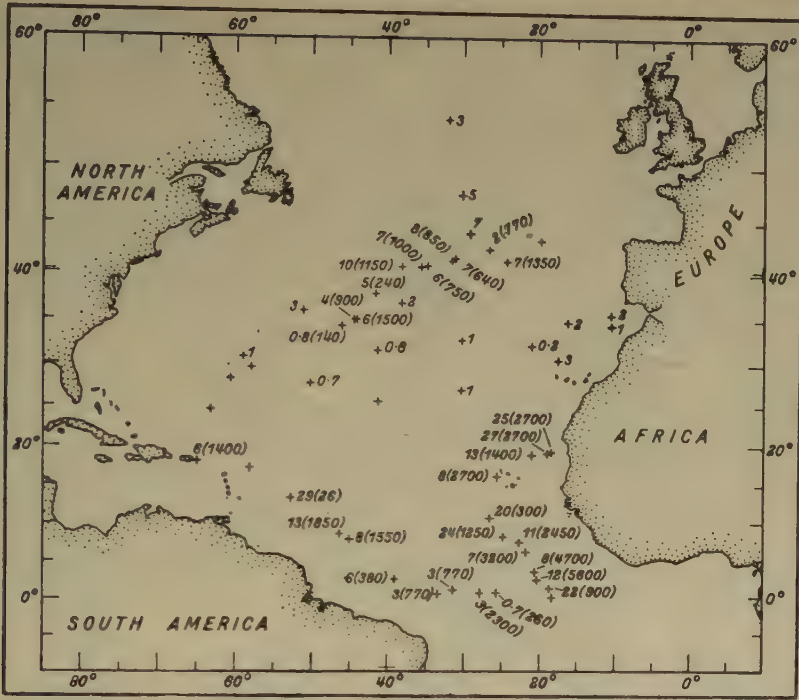

60°
80°
60°
40°
20°
0°
60°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
40°
40°
20°
20°
0°
0°
+3
+5
7
2(770)
8(850)
7(1000)
+7(1350)
10(1150)
7(640)
5(240)
6(750)
3
4(900)
+2
+6(1500)
0·8(140)
+0·8
+1
+0·2
+2
+3
+1
+3
+1
+0·7
+1
25(2700)
27(2700)
13(1400)
8(1400)
8(2700)
+29(26)
20(300)
13(1850)
+8(1550)
24(1250)
11(2450)
7(3200)
8(4700)
6(380)
3(770)
12(5600)
3(770)
22(900)
0·7(260)
3(2300)
80°
60°
40°
20°
0°

Fig. 2. Distribution of *Globigerina eggeri* Rhumbler in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

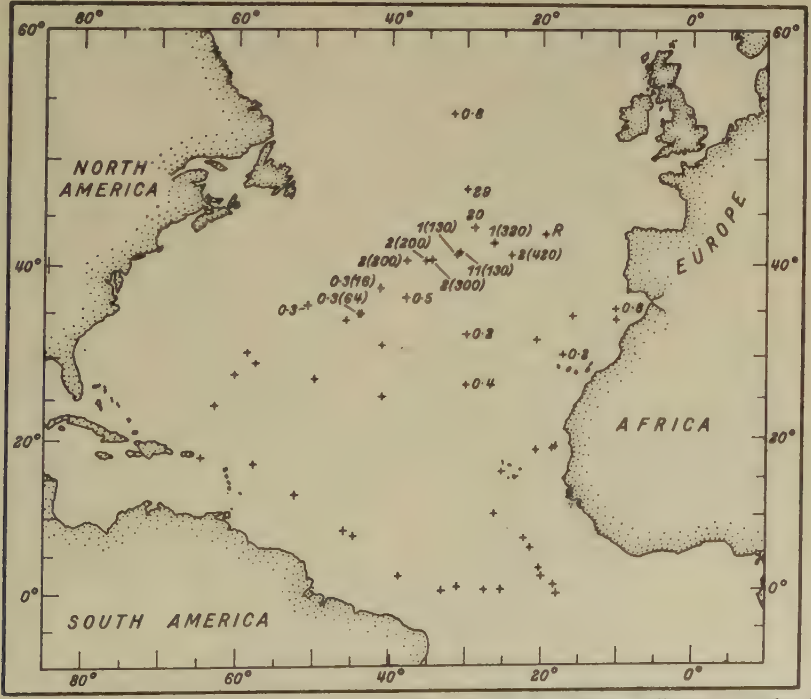

60°
80°
60°
40°
20°
0°
60°
NORTH AMERICA
EUROPE
AFRICA
SOUTH AMERICA
40°
40°
20°
20°
0°
0°
+0·8
+28
20
1(130)
1(320)
+R
2(200)
+2(420)
2(800)
11(130)
0·3(16)
2(300)
0·3(64)
+0·5
0·3
+0·6
+0·2
+0·2
+0·4
80°
60°
40°
20°
0°

Fig. 3. Distribution of *Globigerina pachyderma* (Ehrenberg) in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

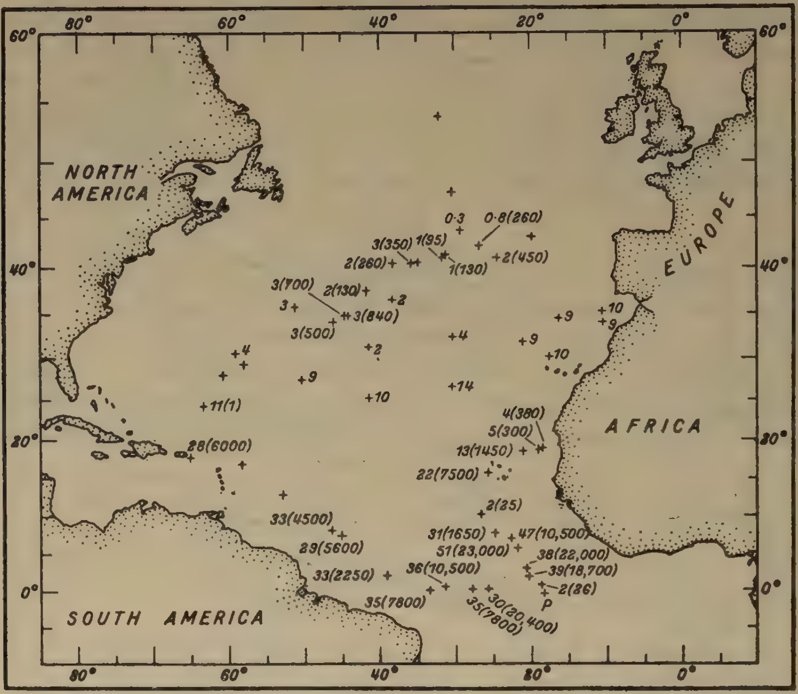

80°
60°
40°
20°
0°
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
0·3
0·8(260)
3(350)
1(95)
2(260)
1(130)
+2(450)
3(700)
2(130)
3
+2
3(840)
3(500)
+9
+10
+9
+4
+2
+9
+10
+4
+9
+14
+10
+11(1)
4(380)
5(300)
13(1450)
22(7500)
28(6000)
2(25)
33(4500)
31(1650)
47(10,500)
29(5600)
51(23,000)
38(22,000)
33(2250)
36(10,500)
39(18,700)
2(26)
35(7800)
30(20,400)
35(7800)
P

Fig. 4. Distribution of *Globigerinoides sacculifera* (H. B. Brady) in surface sediment samples from the Atlantic. First number at each station is per cent to total population of planktonic Foraminifera; second number in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

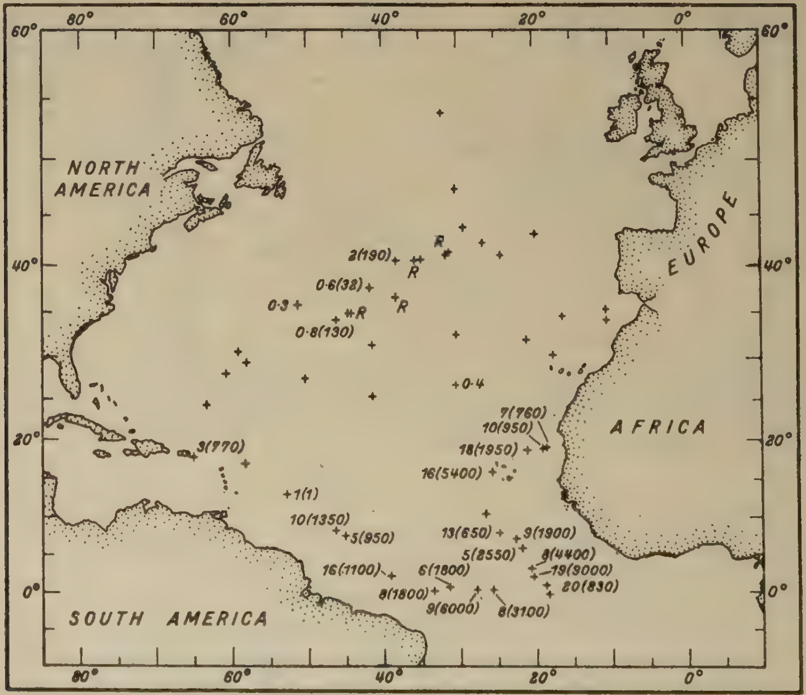

80°
60°
40°
20°
0°
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
R
2(190)
R
0·6(32)
R
0·3
R
0·8(130)
+0·4
7(760)
10(950)
18(1950)
16(5400)
3(770)
+1(1)
10(1350)
+5(950)
13(650)
9(1900)
5(2550)
8(4400)
16(1100)
6(1800)
19(9000)
20(830)
8(1800)
9(6000)
8(3100)

Fig. 5. Distribution of *Globorotalia menardii* (d'Orbigny) in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

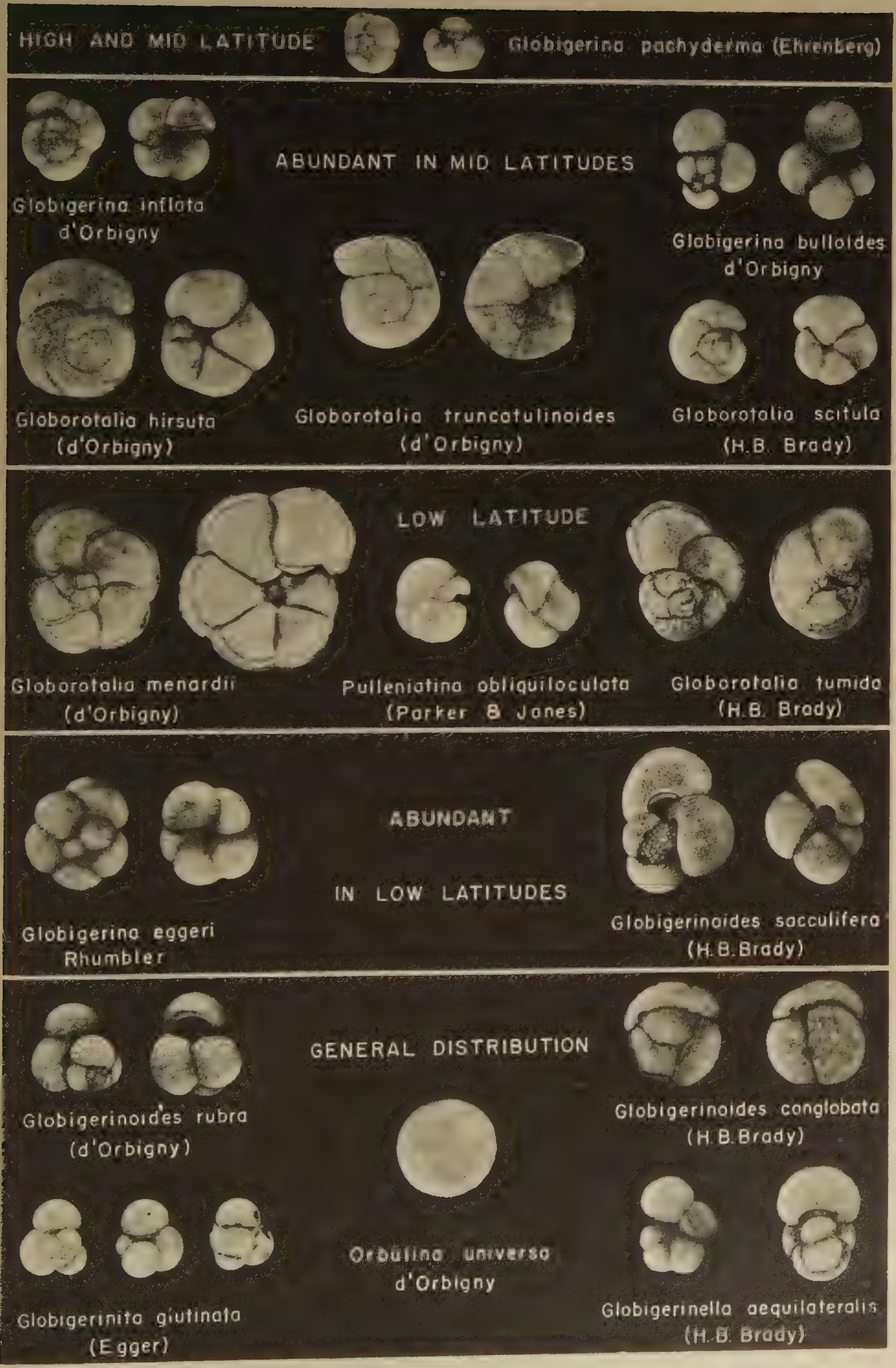
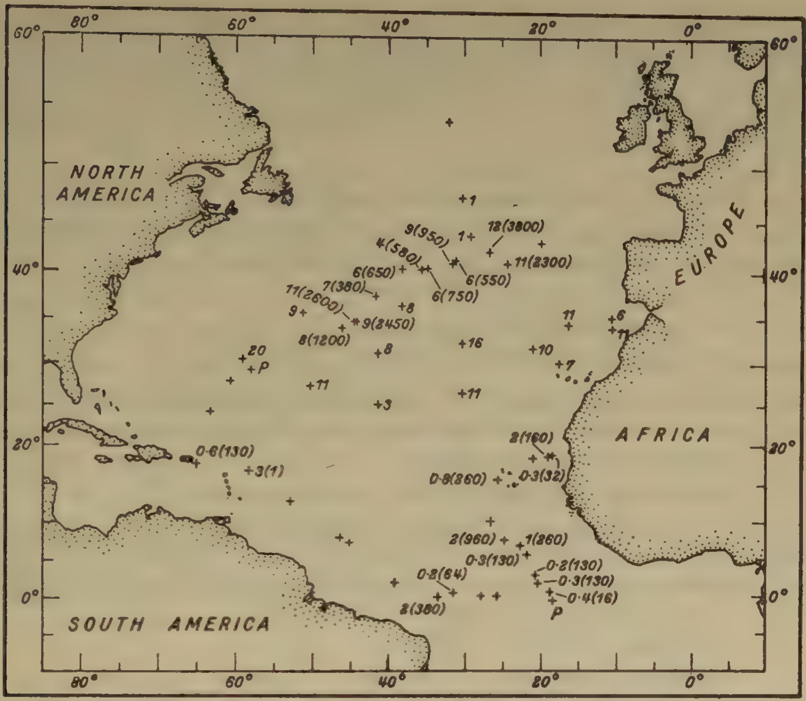

HIGH AND MID LATITUDE
Globigerina pachyderma (Ehrenberg)
ABUNDANT IN MID LATITUDES
Globigerina inflata d'Orbigny
Globigerina bulloides d'Orbigny
Globorotalia hirsuta (d'Orbigny)
Globorotalia truncatulinoides (d'Orbigny)
Globorotalia scitula (H.B. Brady)
LOW LATITUDE
Globorotalia menardii (d'Orbigny)
Pulleniatina obliquiloculata (Parker & Jones)
Globorotalia tumida (H.B. Brady)
ABUNDANT IN LOW LATITUDES
Globigerina eggeri Rhumbler
Globigerinoides sacculifera (H.B. Brady)
GENERAL DISTRIBUTION
Globigerinoides rubra (d'Orbigny)
Globigerinoides conglobata (H.B. Brady)
Orbulina universa d'Orbigny
Globigerinita glutinata (Egger)
Globigerinella aequilateralis (H.B. Brady)

Plate 1. Species of common North Atlantic Foraminifera arranged according to types of distribution.


80°
60°
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20°
0°
60°
40°
20°
0°
NORTH AMERICA
SOUTH AMERICA
EUROPE
AFRICA
+1
1+
9(950)
4(580)
12(3800)
11(2300)
6(550)
6(650)
6(750)
7(380)
11(2600)
+8
9+
9(2450)
8(1200)
+8
+16
+10
11
+6
+11
+7
20
+P
+11
+3
+11
2(160)
0·6(130)
+3(1)
0·8(860)
0·3(32)
2(960)
1(260)
0·3(130)
0·2(130)
0·3(130)
0·2(64)
0·4(16)
2(380)
P

Fig. 6. Distribution of *Globorotalia truncatulionoides* d'Orbigny in surface sediment samples from the Atlantic. First number at each station is per cent of total population of planktonic Foraminifera ; second number, in parentheses, is estimated number of specimens. (After PHLEGER, PARKER and PEIRSON, 1953).

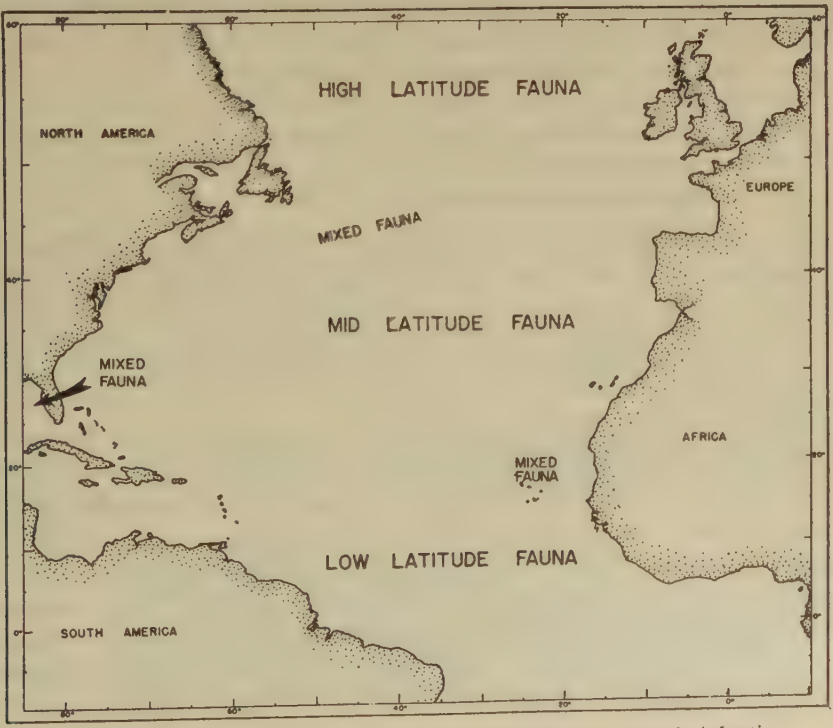

HIGH LATITUDE FAUNA
NORTH AMERICA
EUROPE
MIXED FAUNA
MID LATITUDE FAUNA
MIXED FAUNA
AFRICA
MIXED FAUNA
LOW LATITUDE FAUNA
SOUTH AMERICA

Fig. 7. Generalized facies of planktonic Foraminifera in North Atlantic.

believed to represent as good a generalization as can be made at the present time, but it must be realized that these are based on very few samples from so large an area, except for the tropical region covered by SCHOTT (1935). The distributions listed by PHLEGER *et al.* (1953, p. 71) are as follows (see Plate 1 for illustrations of the species) :

" 1. The following species seem to be characteristic of low latitudes, less than 20° N. Lat., where they occur in relatively high frequencies ; they also occur in low frequencies at a few stations in mid-latitudes in the central Atlantic :

Globorotalia menardii (d'Orbigny)
G. tumida (H. B. Brady)
Pulleniatina obliquiloculata (Parker and Jones)

2. The following species occur in much greater abundance in low latitudes, although they occur at most of the stations (studied by the authors) :

Globigerina eggeri Rhumbler
Globigerinoides sacculifera (H. B. Brady)

3. *Globigerina pachyderma* (Ehrenberg) is confined to high and mid-latitudes.

4. The following species are more abundant in mid-latitudes although they also occur (in much lower frequencies) in low latitudes :

Globigerina bulloides d'Orbigny
G. inflata d'Orbigny
Globorotalia hirsuta (d'Orbigny)
G. scitula (H. B. Brady)
G. truncatulinoides (d'Orbigny)

5. The following species are universally distributed in approximately uniform frequencies within the area covered in this report :

Globigerinella aequilateralis (H. B. Brady)
Globigerinita glutinata (Egger)
Globigerinoides conglobata (H. B. Brady)
G. rubra (d'Orbigny)
Orbulina universa d'Orbigny

These data, and also data from OVEY (in WISEMAN and OVEY, 1950 and SCHOTT 1935) seem to establish clearly what may be termed high-latitude, mid-latitude, and low-latitude faunas in the North Atlantic. Occurrences of a few species characteristic of these distributions are shown in Figs. 1 to 6. It is presumed that similar geographic faunas also occur in the Pacific, but the reliable data are too few in that region to make any generalization.

These distributions have been attributed to the ecological effect of surface ocean temperature by many workers, but there is no good evidence of this. This conclusion is based largely on the occurrence of different faunas in areas where different surface surface temperatures occur, and the fact that temperature is an important factor in affecting distributions of other organisms. It does not seem valid to consider that temperature is the only important ecologic factor affecting these distributions. Other factors which are of possible ecologic importance are salinity, nature and amount of food, water chemistry such as trace elements, pH and eH, depth, hydrostatic pressure (see OPPENHEIMER and ZOBELL, 1952), turbidity, turbulence, substrate (if there is a benthonic stage), currents, biologic competetion, predators, disease, etc. Physiological experimentation will be necessary to determine the relative importance of these various factors. Preliminary experiments on benthonic types, such as the frequently cited work of Myers (1935a, 1935b, 1936, 1937, 1943) do not necessarily have much application to these problems. His studies are mostly confined to benthonic Foraminifera, and studies on one species or even the fauna from one environment do not necessarily apply to another species or another environment. It seems probable that an infinite amount of study and experimentation must precede any real understanding of the effects of various enviromental factors on species and faunas of Foraminifera.

The writer recently has adopted a generalization which seems to aid in explaining the distributions of some of these faunas. This is the ecologic water-mass, based in part on a common concept in physical oceanography in which various marine water-masses are differentiated by some of their physical characteristics. An ecologic water-mass may be defined as any body of marine water which has a uniform ecologic effect and supports a uniform assemblage of organisms. On this basis it may be said that the three geographic foraminiferal faunas in the North Atlantic are differentiated because they inhabit and are adapted to three different water-masses. This is essentially true in the sense of physical oceanography and it appears reasonable from an ecological point of view.

MIXED PLANKTONIC FAUNAS

Mixing of planktonic faunas is expected to occur wherever there is mixing of the different water-masses which these different faunas inhabit. One of the most obvious examples of this is the transport of the low-latitude species, such as *Globorotalia menardii* (d'Obigny), into mid-latitudes by the Gulf Stream System (see figure 5). The transport of warm water into mid and high latitudes by this mechanism is well-known. Occasional masses detach themselves from the Gulf Stream and invade far beyond what appears to be the normal path of the currents. The presence of such low-latitude species as *Globorotalia menardii* (d'Orbigny) and *Globigerinoides sacculifera* (H. B. Brady) in the southern Gulf of Maine (Peirson, personal communication) undoubtedly is the result of such a mechanism. Occurrence of similar low-latitude species in pre-modern sediments, presumably Pleistocene in age, under Boston Harbor suggests that this mechanism has been occurring for some time (Phleger, 1949 ; Stetson and Parker, 1942).

The Gulf Stream is bounded on the north by sub-Arctic water. The position of this boundary is known to shift through a considerable distance and there is mixing of the two water-masses in the boundary area. The sediments underlying this region contain a mixed high and mid-latitude fauna with some low-latitude species in low frequencies. A sample reported by Phleger and Hamilton (1946, plate 1) from this boundary region near Georges Bank contains the following species in relative abundance :

Globigerina eggeri Rhumbler (low-latitude)
G. inflata d'Orbigny (mid-latitude)
G. pachyderma (Ehrenberg) (high-latitude)
Globigerinoides rubra (d'Orbigny) (low and mid-latitude)
Globorotalia menardii (d'Orbigny) (low-latitude)

Other samples in the collections of the Marine Foraminifera Laboratory from this general area have a similar faunal composition. Such a natural mixture of these faunal elements could only occur at the position of the Arctic or Antarctic convergence ; low-latitude species are expected to be more abundant on the upstream side of the warm-water current in such a convergence area.

Figure 1 shows a high concentration of *Globigerina bulloides* d'Orbigny, a typical mid-latitude species, at a few stations off the west coast of Africa between Cape Verde and Cape Blanco. Fig. 5 shows a high frequency of *Globorotalia menardii* (d'Orbigny), a low-latitude form, at the same stations. The occurrence of these two species together in high frequencies is an apparently anomalous association. These mixed assemblages occur in the area of the Equatorial Counter Current and in general where it combines with water from the Canaries Current to form the North Equatorial Current. This also is the position of the North-east Trade Winds, which provide most of the force moving the North Equatorial Current. It is believed that these mixed faunas occur because the low-latitude forms are being contributed from the Counter Current water and the mid-latitude forms are from the mid-latitude water of the Canaries Current. Mixed faunas in these latitudes are expected to occur only on the eastern sides of oceans in a convergence area. There is a water divergence on the opposite side of the North Atlantic and a pure low-latitude fauna is expected.

Distributions of several species of planktonic Foraminifera in the northern Gulf of Mexico are shown on Figs. 8 to 13. These distributions are based on occurrences in more than 700 surface sediment samples from this region and are believed to give an accurate general picture of occurrences. These may be compared with the distributions of the same species in the North Atlantic on Figs. 1 to 6. It is seen that the Gulf of Mexico fauna is a mixed low-latitude and mid-latitude one. An illustration of the mixed nature of this fauna is the association of the following species in relatively high frequencies : *Globigerina bulloides* d'Orbigny, *G. eggeri* Rhumbler, *Globigerinoides sacculifera* (H. B. Brady), *Globorotalia menardii* (d'Orbigny), *G. truncatulinoides* (d'Orbigny), and *Pulleniatina obliquiloculata* (Parker and Jones). This is interesting, inasmuch as most or all of the water apparently being supplied to the Gulf of Mexico appears to be from the North Equatorial Current system and should contain a pure low-latitude fauna. It is expected that the Gulf of Mexico should be populated with this assemblage. The writer suggests two possible explanations for the presence of the mixed fauna : (1) Mid-latitude water carrying its indigenous planktonic fauna may enter the Gulf of Mexico around the Florida Peninsula. It is possible that this water enters and is dispersed by a coastal current system flowing west and northwest. (2) The mid-latitude fauna may have invaded this region during one of the Pleistocene glacial stages, or at some other time in the past, and may now be a " relict " fauna.

Further examination of the distribution (Figs. 8 to 13) shows two types of distribution in the northern Gulf of Mexico. *Globigerina eggeri* Rhumbler, *Globigerinoides sacculifera* (H. B. Brady), and *Globorotalia menardii* (d'Orbigny) generally occur in highest frequencies in the southeast part of the area, opposite Yucatan Strait where the tropical water-mass enters the Gulf of Mexico. The frequencies of these species generally decrease toward the northwest. This suggests that the Gulf of Mexico is being stocked with these three species as a result of their being introduced with the low-latitude water-mass which they inhabit. These low-latitude species would

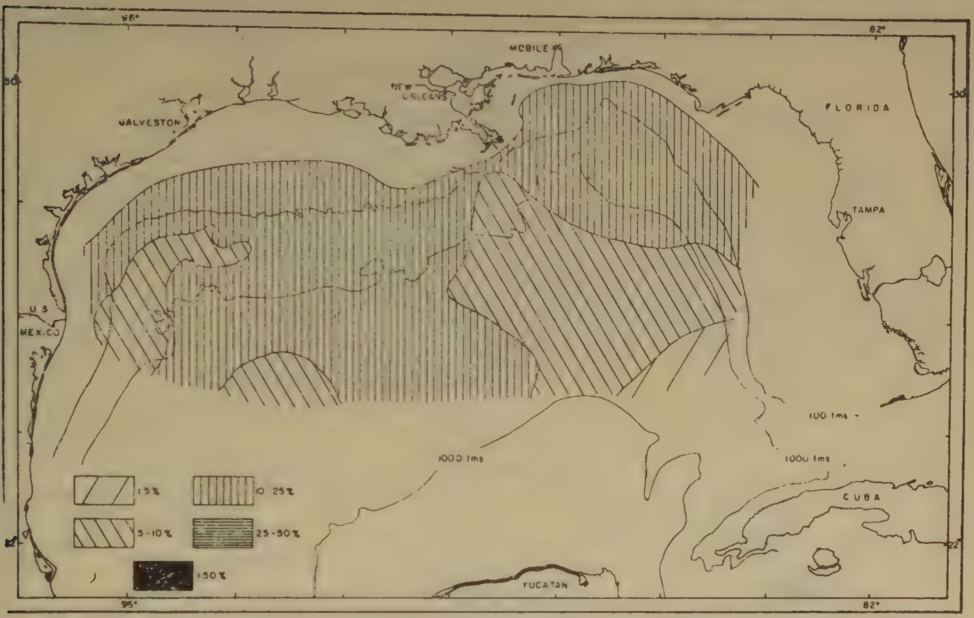
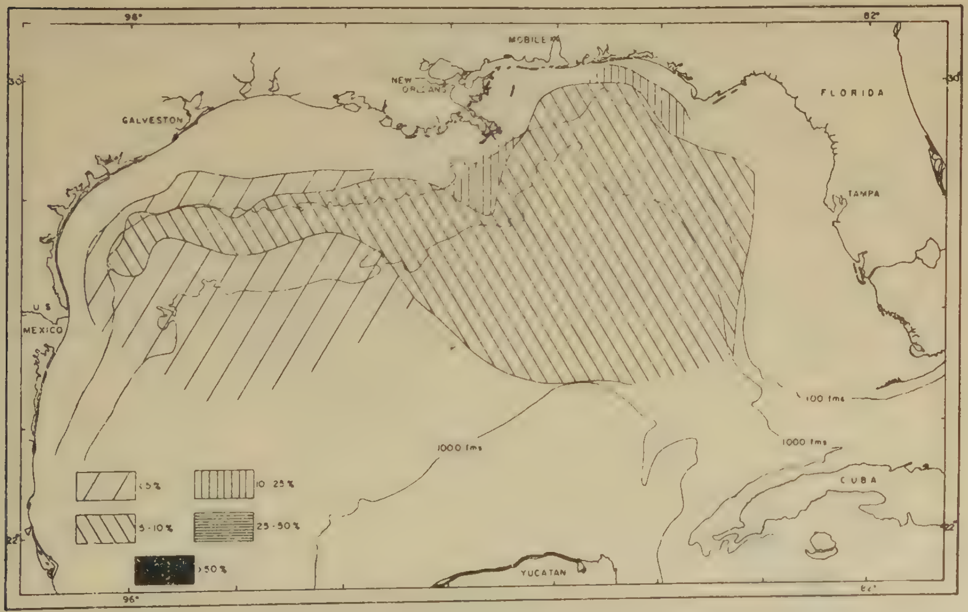

96°
82°
30
MOBILE
NEW ORLEANS
GALVESTON
FLORIDA
TAMPA
U S
MEXICO
100 fms
1000 fms
1000 fms
CUBA
YUCATAN
<5%
10-25%
5-10%
25-50%
>50%
22
95°
82°

Fig. 8. Distribution of *Globigerina bulloides* d'Orbigny in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).


96°
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30
MOBILE
NEW ORLEANS
GALVESTON
FLORIDA
TAMPA
U S
MEXICO
100 fms
1000 fms
1000 fms
CUBA
YUCATAN
<5%
10-25%
5-10%
25-50%
>50%
22
96°
82°

Fig. 9. Distribution of *Globigerina eggeri* Rhumbler in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b and PARKER, 1954).

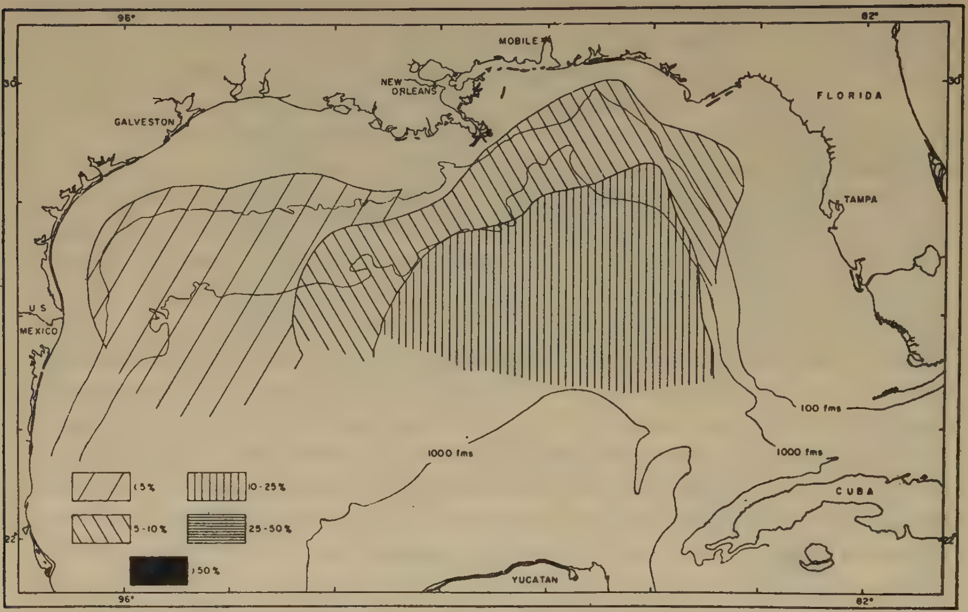

96°
82°
30°
22°
MOBILE
NEW ORLEANS
GALVESTON
FLORIDA
TAMPA
U S
MEXICO
100 fms
1000 fms
1000 fms
CUBA
YUCATAN
<5%
5-10%
10-25%
25-50%
>50%

Fig. 10. Distribution of *Globigerinoides sacculifera* (H. B. Brady) in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

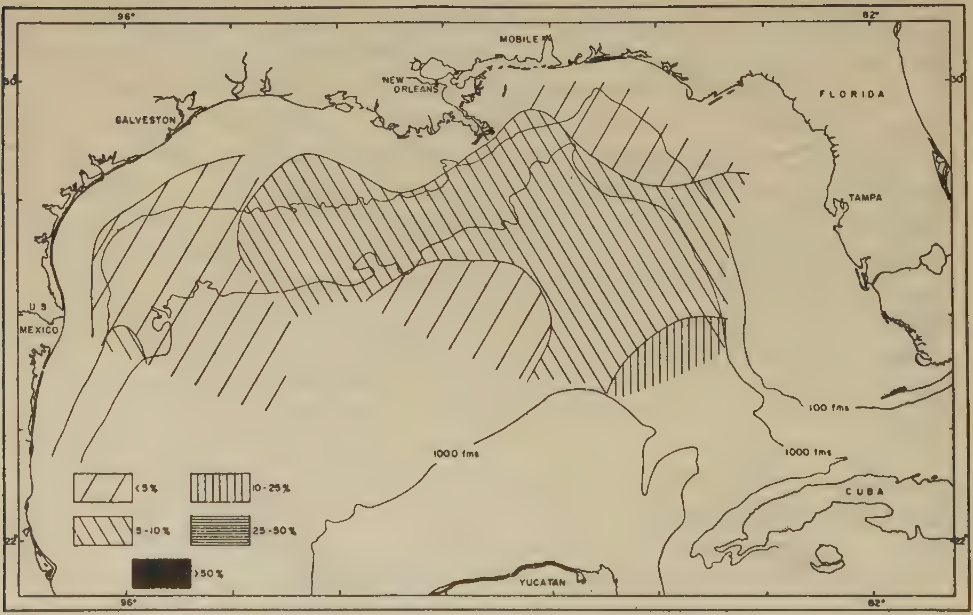

96°
82°
30°
22°
MOBILE
NEW ORLEANS
GALVESTON
FLORIDA
TAMPA
U S
MEXICO
100 fms
1000 fms
1000 fms
CUBA
YUCATAN
<5%
5-10%
10-25%
25-50%
>50%

Fig. 11. Distribution of *Globorotalia menardii* (d'Orbigny) in northern Gulf of Mexico in per cent total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

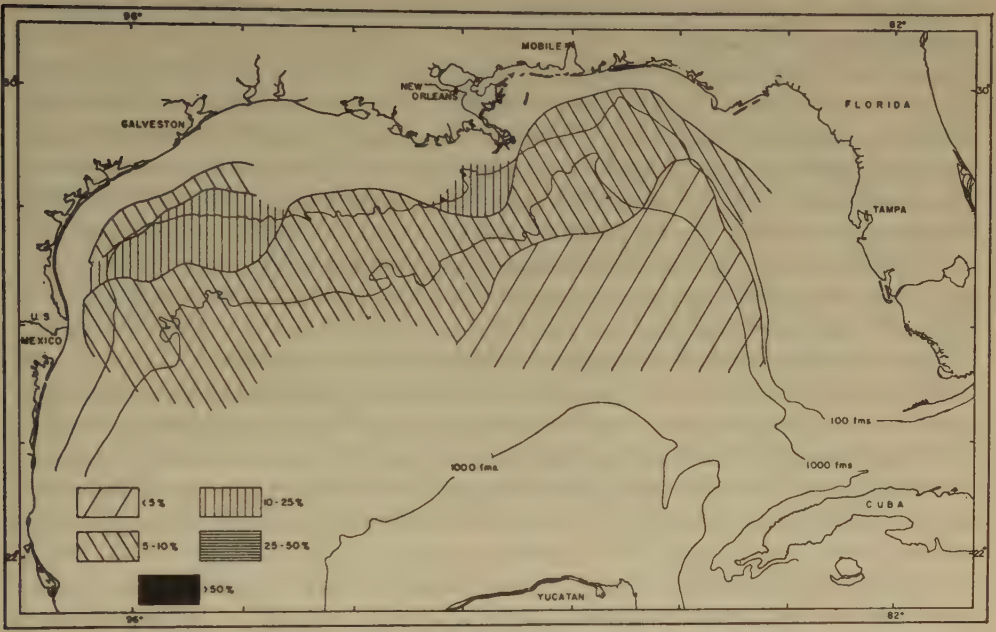
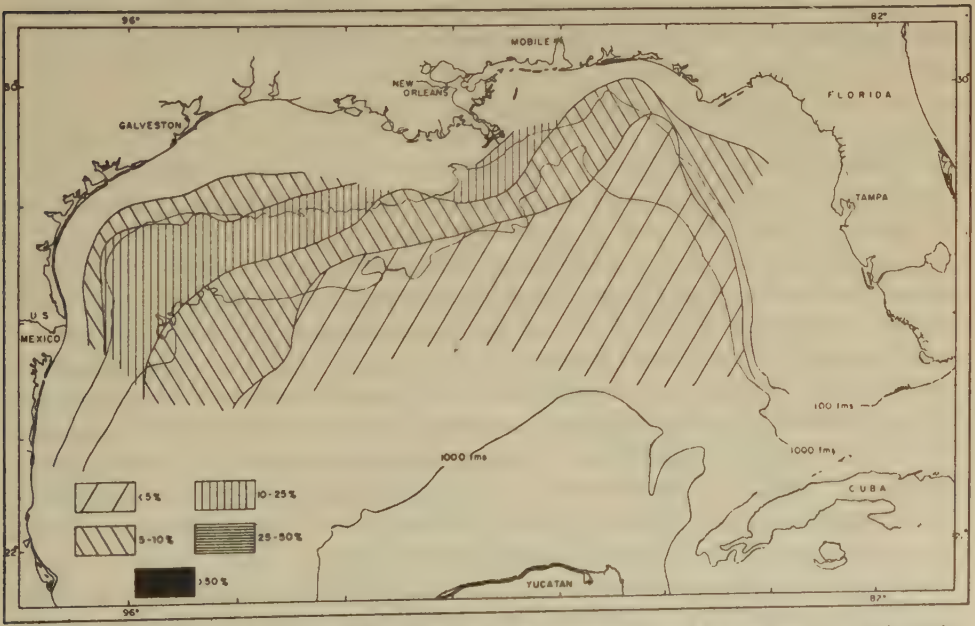

96°
82°
MOBILE
NEW ORLEANS
GALVESTON
FLORIDA
TAMPA
U S
MEXICO
100 fms
1000 fms
1000 fms
CUBA
YUCATAN
<5%
5-10%
10-25%
25-50%
>50%
30°
22°

Fig. 12. Distribution of *Globorotalia truncatulinoides* (d'Orbigny) in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).


96°
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MOBILE
NEW ORLEANS
GALVESTON
FLORIDA
TAMPA
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MEXICO
100 fms
1000 fms
1000 fms
CUBA
YUCATAN
<5%
5-10%
10-25%
25-50%
>50%
30°
22°

Fig. 13. Distribution of *Pulleniatina obliquiloculata* (Parker and Jones) in northern Gulf of Mexico in per cent of total population of planktonic Foraminifera. (Based on data from PHLEGER, 1951b, and PARKER, 1954).

probably be of uniformly high frequencies in the region if low-latitude water filled the entire area of the basin.

The characteristically mid-latitude species, *Globigerina bulloides* d'Orbigny and *Globorotalia truncatulinoides* (d'Orbigny), are more abundant in the northwesternmost Gulf of Mexico and decrease in frequency toward the east and south. The centre of highest frequency does not appear to be related to any immediate source of mid-latitude water from the Atlantic. It is possible that these species were introduced into the Gulf of Mexico in abundance during some earlier time when mid-latitude water may have been abundantly supplied to the basin. They may have been able to survive and reproduce in abundance because the northwest Gulf of Mexico assumes characteristics of mid-latitude water during the winter season. The distribution of the low-latitude and mid-latitude species suggests that the water in the northwest behaves as a separate mass. This is in agreement with a suggestion made by R. C. REID (personal communication) that the water circulation in the western Gulf of Mexico is in the form of a large eddy and that there may be little communication with the water in the eastern part of the basin. It is apparent from the distributions of the planktonic Foraminifera that some water interchange occurs, but it may be relatively small.

Pulleniatina obliquiloculata (PARKER and JONES) is a low-latitude species which occurs in the area immediately north of the Yucatan Strait (Fig. 13) in frequencies similar to those in the North Atlantic. It is more abundant, however, in the northwest Gulf of Mexico, constituting up to 25% or more of the planktonic Foraminifera at numerous stations. These data also suggest that this species became established in this area during previous conditions. It is suggested that *P. obliquiloculata* (Parker and Jones), *Globigerina bulloides* d'Orbigny, and *Globorotalia truncatulinoides* (d'Orbigny) may be in part relict in the northwest Gulf of Mexico.

PLANKTONIC FORAMINIFERA IN DEEP-SEA CORES

(a) *Stratigraphic Sequences*

Planktonic Foraminifera have been used by several workers to interpret the stratigraphy of deep-sea cores. It is assumed that the fauna at the top of such a core has accumulated during the present conditions obtaining at the place where the core was collected. Differences between the faunas occurring at lower levels in the core and those at the top of the core are interpreted in terms of what is known of distributions of the modern assemblages discussed above. Interpretations which have been made are in terms of surface water temperatures, on the assumption that different assemblages reflect differences in these temperatures. These differences in surface water temperatures at certain times during the past have been taken to represent glacial and interglacial stages and/or substages during the Pleistocene epoch; moreover, some authors have attempted correlations of the faunal sequences with Pleistocene chronology in Europe and North America.

It is seen in the discussion above that knowledge of the environments under which various planktonic Foraminifera live and are deposited in the sediments is very incomplete. Any conclusions about conditions represented by older faunas, therefore, must be considered as approximations only. This should be realized in evaluating any generalizations based on faunal sequences in submarine cores.

It has been widely recognized that in many deep-sea cores there are one or more faunas of planktonic Foraminifera below the surface which are unlike the modern fauna and are similar to those occurring at a higher latitude than that of the core being studied. The inference that such faunas lived when the water-mass at the core location was different and like that now prevailing at a higher latitude seems to be a reasonable one. It also appears reasonable that one of the characteristics of such a higher-latitude water-mass is lower surface temperature conditions than those in a lower-latitude water-mass. These higher-latitude faunas in cores may be referred to as " colder " faunas for convenience, but it should be realized that this is essentially an empirical, descriptive term. The colder-water faunas from low-latitude cores are mid-latitude faunas and those from mid-latitudes are high-latitude faunas. Recognition of such colder-water faunas in cores from high latitudes is difficult or impossible at the present stage of our knowledge.

These colder faunas of Foraminifera have been reported from several areas. SCHOTT (1935) recognized a higher-latitude fauna in the lower part of numerous cores collected from the tropical Atlantic. The colder fauna was distinguished principally by the absence of *Globorotalia menardii* (d'Orbigny), which is abundant in the surface samples in this region. CUSHMAN and HENBEST (1940) differentiated colder-water funas in a series of cores from approximately 50° N. Lat. in the Atlantic. Several cold-water faunas are recorded from the Atlantic continential slope of the northeastern United States by PHLEGER (1939, 1942), from approximately 37° N. Lat. to 41° N. Lat. Additional reports from the Atlantic are as follows : in one core from the Caribbean Sea (PHLEGER, 1948), in numerous cores from the northwest Gulf of Mexico (PHLEGER, 1951b), in several cores collected by ERICSON, EWING and HEEZEN (1952) from the western North Atlantic, in three cores from the equatorial Atlantic studied by SCHOTT (1952), and in two cores from the western basin of the Atlantic at 40° N. Lat. (PHLEGER and HAMILTON, 1946). STUBBINGS (1937) studied six cores containing alternating warm and cold faunas from the Arabian Sea and PHLEGER (1947) reports a similar sequence from the Tyrrhenian Sea. Arrhenius (1952) recognized several Pleistocene stages in the eastern equatorial Pacific based in part on sequences of planktonic Foraminifera.

(b) *Correlation of Faunas from Deep-sea Cores.*

In most of the cores studied there are sequences of alternating cold- and warm-water faunas, interpreted as reflecting glacial and interglacial stages represented on land. The problem of correlation between cores within or between different oceanic areas arises in connection with making generalizations about the marine conditions of the Pleistocene. It is difficult, and may be impossible, to correlate widely separated sequences with the present information and understanding of the problem. BRAMLETTE *et al.* (1940) have correlated most of their cores on the basis of stratigraphic distribution of volcanic ash and marine zones. ARRHENIUS (1952) has correlated his core sequences in the eastern Pacific on the basis of several biological and chemical characteristics. The use of several sedimentary criteria appears to be more reliable than the use of faunas alone, but the faunal composition also should be used in such an attempt.

PHLEGER *et al.* (1953, p. 111) have discussed the problem of correlation in deep-sea cores by means of planktonic faunas of Foraminifera, as follows : " The species are modern ones and although minor variations having age significance may be established with further, detailed study, there are no presently recognized extinct species or varieties in this age range (post-Miocene) . . . . The only apparent general means of correlation of these microfaunas is by matching supposed similar events based upon faunal interpretations. It can be inferred, for example, that the uppermost ' colder-than-modern " faunas in all the cores are correlatives. Likewise, successively lower " warm "- and " cold "-water funas in the various cores have been interpreted as having been deposited at the same time. Correlation has been based, therefore, on matching a series of events which in turn are based on ecological interpretations of the microfaunas.

" The faunal variations in a core may be quite real but their significance can be questioned. The differences between low, mid, and high-latitude faunas have been correlated with the distribution of oceanic surface isotherms. This correlation is imperfect and is based upon few and relatively unreliable data. It is assumed that surface water temperatures are of primary ecologic importance, and this is not necessarily true. It is possible that some of the faunal variations may be caused by local water-mass migrations which are not necessarily of very great over-all significance." This latter suggested complication may be most pronounced in a region such as the northern edge of the Gulf Stream. It is now well-known that the position of the Gulf Stream varies considerably (ISELIN and FUGLISTER, personal communication) and also that there are eddies, counter-currents, and numerous bodies of water which have been detached from the main water-mass. Certain sequences of cold- and warm-water planktonic Foraminifera collected from this region may be suspected of reflecting such water movements.

It seems probable that the lower boundary of the modern fauna is to be correlated between cores, but only in those where this boundary can be recognized with some assurance. Also, some recent work has suggested that some variations within certain species may have a time significance. It is reported by BOLLI (1950), for example, that direction of coiling in *Globorotalia* may be of value. According to BOLLI (*op. cit.*, p. 87)" . . . . changes in coiling in a number of species of *Globorotalia* . . . . during their vertical range . . . . show that certain rules may govern the evolution of these species insofar as the nature of the coiling is concerned. Those specimens which coil in either direction in approximately equal numbers are usually the earlier representatives of a species . . . . The stratigraphically younger representatives of a species appear to change abruptly to almost entirely a sinistral or dextral coiling . . . "

ERICSON (1953) has studied stratigraphic distribution of the direction of coiling of *Globorotalia truncatulinoides* (d'Orbigny) in several cores from the Atlantic. His results indicate different ratios of right and left coiling at various times during the recent past and his preliminary results show this to be a promising tool for correlation. PHLEGER *et al.* (1953) found that *Globorotalia tumida* (H. B. Brady) *s.s.* may be of some value in correlation of cores from the North Atlantic. This species appears to be no older than their last cold-water fauna in the cores where it occurs, and may thus be a guide to late glacial and post-glacial times. ERICSON has found (personal communication) that *Globorotalia tumida* (H. B. Brady) var. *flexuosa* (Koch) has a definite upper limit in many of his cores, and may be no younger than the warm-water fauna preceding the present one. The distribution of this variety has been studied in the Atlantic cores collected by the Swedish Deep-Sea Expedition, described by PHLEGER *et al.* (*op. cit.*). We have found that the upper stratigraphic range of this variety is limited approximately to the warm fauna preceding the present one in some cores, and occurs in what is presumed to be the post-glacial faunas in others. It is possible, however, that frequency distributions of this form will be useful in future studies. All these preliminary studies suggest that consistent variations within species may prove to be of great value in future correlations of faunas in deep-sea cores.

(c) *Rate of Sedimentation*

One method of estimating the absolute rate of deep-sea sedimentation is based on the thickness of sediment which has accumulated during post-glacial time, determined on the basis of foraminiferal sequences. SCHOTT's (1939) rates were based on the assumption of 20,000 years for the length of post-glacial time and varied from 0·5 to 3·3 cm/1,000 yrs. in the Atlantic. The estimate of 20,000 years for post-glacial time may be too long, and also the ocean may not have responded to climatic changes in the same manner or at the same time as the lands ; nevertheless, this is one of the best methods available for measuring rate of deep-sea deposition.

It seems likely that relative rates of sedimentation may be estimated if time correlations between cores are possible. PHLEGER *et al.* (1953, pp. 115-116) have indicated that this may be possible in some of their mid-latitude cores between 40°N. Lat. and 50° N. Lat. These are based on the assumption that a series of events presumed to be similar may be correlated. The general observation may be made that there are apparent differences in relative sedimentation rates, that in some places this rate was very high while at other places it was extremely low, and that the sedimentation rates may vary with time.

It may eventually be possible to calculate absolute rates of deep-sea deposition of sediment using rates of production of planktonic Foraminifera. This would be based on the Foraminifera as a source of sedimentary material exclusively marine in origin and independent of materials of terrestrial origin. Such a method would require specific data on rate of production of these forms, some of which may be obtained by frequent sampling of the standing crop over a long period of time, and much of the information would be required from experimental culturing.

(d) *Generalizations to be made from Sequences of Core Foraminifera.*

The widespread occurrence of a cold fauna beneath the modern one strongly suggests that it is to be generally correlated, as discussed above. A part of this lower fauna contains elements at present adapted to higher latitudes at all places where such faunas are known and adequately reported, and thus they are presumed to represent lower surface-water temperatures. This suggests that sea-surface temperatures were generally cooler at all latitudes during the deposition of the " late-glacial " assemblages. PHLEGER (1951b, pp. 78-79) has attempted to assign approximate surface-temperature values to lower, cold-water core faunas and transition core faunas in the northwest Gulf of Mexico :

" Transition faunas (between warm and cold-water faunas) . . . . contain elements suggestive of the present North Atlantic continental slope region, between approximately Cape Henry and Cape Cod.

" Surface waters over the slope of the region from Cape Henry to Cape Cod have temperatures approximately as follows : maximum surface temperatures (August) range from about 77°F in the south to 65°F in the north ; minimum surface temperatures (February) range from about 60°F in the south to 45°F in the north . . . . The ' transition fauna ' between the upper and lower faunas in the cores may have accumulated under surface water temperature conditions similar to those given. The lower core fauna may have accumulated under somewhat colder conditions, but no so cold as in present Arctic waters."

The presence of alternating cold- and warm-water faunas suggests alternating times of relatively colder and warmer sea surface-water temperatures. Various attempts have been made to correlate these presumed cold- and warm-water conditions with stages and/or substages of the Pleistocene known in North America and in Europe. Such correlation is pure speculation based on very incomplete evidence and may be misleading. An attempt has been made by OVEY (1949, p. 230) to correlate data given by PHLEGER (1948) on a core from the Caribbean Sea with the Pleistocene glacial chronology and stage names of North America. This has been copied by SIGAL (1952, p. 294) in his admirable section on Foraminifera in *Traité de Paléontologie*, and thus has assumed a certain reliability. The diagram used by these authors is based upon speculation by the original investigator (PHLEGER, 1948, pp. 7-8) which is subject to all the uncertainties discussed previously. It is probably incorrect to assign North American chronological names to such material regardless of its possible reliability or unreliability.

Mixed low-latitude and mid-latitude planktonic faunas of Foraminifera have been reported in lower samples of five deep-sea Atlantic cores by PHLEGER *et al.* (1953, pp. 108-109). It is shown above that similar mixed faunas occur in the eastern Atlantic at the convergence of the tropical Counter Current and the mid-latitude water of the Canaries Current system in the eastern Atlantic at the position of the North-east Trades at 20-25°N. Lat. The lower mixed faunas in the cores are also from the eastern Atlantic, but occur at 0-7° N. Lat. " These data strongly suggest that at some time during the past the convergence area has shifted southward at least 10 or 15° of latitude. If this suggested interpretation is correct, then the position of the North Equatorial Current and also the Trade Winds belt may also have shifted southward by this amount at some times during the past.

" The implications of this southward shift of the Trade Winds and current system are of considerable interest. It may be presumed that these faunas represent a cold-water phase and some glacial stage of the Pleistocene. It may suggest that the northern hemisphere mid and low-latitude wind belts were displaced toward the southern hemisphere during the Pleistocene, or it may indicate a telescoping of the wind circulation in equatorial regions. The effect of such a modification of the wind system would be expected to have far-reaching effects on the Atlantic water circulation and therefore far-reaching effects on continental climates." (PHLEGER *et al., op. cit.*, p. 120).

ARRHENIUS (1950, p. 87) in connection with his work on deep-sea cores from the eastern Pacific states : " The results from the investigations of the east Pacific sequences . . . . indicate great constancy in the path of the Counter Current during Pleistocene time . . . . The lack of significant displacements of the Counter Current during Pleistocene time appears to be a definite proof that the climatic changes were synchronous in the northern and southern hemispheres." It is apparent from these conflicting conclusions that more study is required on this interesting phase of deep-sea research.

DISPLACED FAUNAS AND THEIR IMPLICATIONS

The occurrence of sands in occasional deep-sea deposits has been recognized by several people but only in recent years has the significance of these deposits been appreciated. It is well-known that coarse-grained sediments, i.e. sands, are generally characteristic of nearshore deposits. Their occasional presence in deep water could mean : (1) that they were deposited in shallow water and have been displaced into deep water, (2) that they were deposited when the deep-sea areas in which they are found were much shallower, or (3) that there are unknown processes in the deep-sea which act to produce occasional deposits of sand.

Benthonic Foraminifera have proved to be of great value in studying the origin of these deep-sea sands in proving that such sands have been displaced from shallow into deep water. The depth displacement of these forms is based on what is known of depth distributions of benthonic Foraminifera, based on studies such as those by NATLAND (1933), PARKER (1948), COLOM (1952), LOWMAN (1949), PHLEGER (1942, 1951a), and WALTON (1954). Tests of Foraminifera may be considered an integral part of their enclosing sediment and where the material is displaced out of its normal depth-habitat the Foraminifera constitute at present the most reliable record of its former environment.

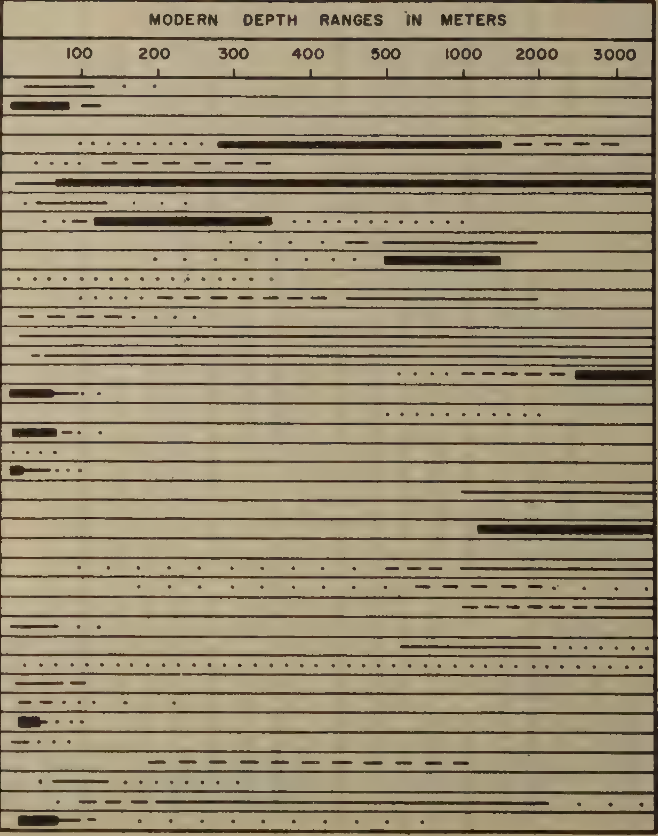
The displaced faunas recorded in two cores collected from the Sigsbee Deep in the Gulf of Mexico may be cited as an example of these displaced microfaunas. The data on these faunas are listed by PHLEGER (1951a, fig. 31 ; 1951b, fig. 7) ; Table 1 shows some of these data along with known depth distributions of all the benthonic species occurring in the cores and from the same area. An examination of Table 1 shows rather striking differences between the benthonic assemblage in the upper parts of cores 335 and 336 from the Gulf of Mexico and in the lower parts of the cores. The upper fauna is almost exclusively composed of the following : *Cibicides wuellerstorfi* (SCHWAGER), *Eggerella bradyi* (CUSHMAN), *Epistominella decorata* (PHLEGER and PARKER), *Eponides polius* (PHLEGER and PARKER), *E. tumidulus* (H. B. BRADY), *Glomospira charoides* (JONES and PARKER), and *Nonion pompilioides* (FICHTEL and MOLL). These forms characterize the normal assemblage in this area at depths greater than 2,000 m, as seen by examining the range-chart, and the fauna is normal for the depth at which it was collected. The lower core fauna, on the other hand, contains species which normally occur at a variety of depths, and many of which are from depths shallower than approximately 100 m. This demonstrates that such species, from depth-ranges shallower than 2,000 m, and their enclosing sediment have been displaced downslope from their normal habitat. The presence of deep-water forms, along with shallow-water species, is evidence that the material was deposited at about the same depth at which it now occurs. The shortest distance to a depth of 100 m is approximately 80 nautical miles.

Several displaced faunas of benthonic Foraminifera are recorded by PHLEGER *et al.* (1953) from the North Atlantic from near the Canary Islands, near the Cape Verde Islands, and near St. Croix, all areas of known high submarine relief. Two cores off the coast of Brazil at 4,500 m depth have thick sections containing shallow-

Table 1

Foraminifera in selected samples from cores 335 and 336, northwest Gulf of Mexico in per cent of total population of benthonic Foraminifera. (After PHLEGER, 1951a).

	CORE 335 - 3438 m.													CORE 336 - 3530 m.									
Cm. from top of core	0	24	56	105	138	156	168	178	182	186	193	198	214	1	28	41	96	117	133	153	168	189	204
Angulogerina bella								2			1	2								2			
Bigenerina irregularis											1								2				3
Bolivina alata										21										5	5	3	
B. albatrossi												2							4				
B. barbata											5	3								2		3	3
B. lowmani												8										5	
B. striatula spinata								5			3	2											
B. subaenariensis mexicana											3	5								5		11	
Bulimina aculeata												1							13	5		5	8
B. alazanensis											3	2							2				3
B. marginata								2			3	2									5		
B striata mexicana								2			1	3										3	5
Cancris oblonga																			2	2			
Cassidulina subglobosa		1									1											5	
Cibicides aff. floridanus	3			3															4	5	2		5
C. wuellerstorfi	11	31	21	15	32	33			5			1	12	47	33	6	11	36			2	5	
Cibicidina strattoni											3	6							4	5	10	11	13
Eggerella bradyi	5		5	5	4	4							4			6	3	6					
Elphidium discoidale								5			31	24							18	25	20	8	30
E. cf. fimbriatulum												1							2				
E. gunteri											1	1							4	5		3	
Epistominella decorata	8	7	19	13	18	7			5		1		4		22	35	21	12	2				
Eponides polius	14	17	5											21									
E. tumidulus	3		9	5	8										11	12	14						
Globobulimina affinis						7	20	10	17	36								15	4	2	2	3	3
Glomospira charoides	25	1												5	11	6	3						
Gyroidinoides altiformis					4											12	3				2	3	
Nonion pompilioides	5	20	19	13	14	11	20						4	5	11		7	6					3
Nonionella atlantica												3							2	2	2		
Osangularia cultur		1	2								1												
Pseudoeponides umbonatus			5	10	4	7										6	3	9	2		2	3	
Rectobolivina advena											3	4									2		
Reussella atlantica								7		7	1								4	2			5
"Rotalia" beccarii parkinsoniana											8	9							4	7	7	3	3
"R." beccarii tepida																			2		2		
"R." translucens								2												2			3
Uvigerina parvula										21		2											
U. peregrina								10	5		5	6							11	2	12	11	5
Virgulina pontoni								5	11			2								2	2		



water Foraminifera some of which must have come from the continental shelf. The sediment containing these faunas probably has been displaced a distance of at least 300 miles.

Ericson *et al.* (1951, 1952) have published preliminary reports on numerous long, deep-sea cores from the North Atlantic. They have generalized on the faunas which occur in sands in these cores as follows (*op. cit.*, 1951, p. 963) : " Foraminifera, though never abundant, are usually present in the coarser sands. . . . There are almost without exception a few species which are characteristic on the continental shelf and slope sediments, such as *Elphidium incertum*, *Globobulimina auriculata*, and *Nonion labradoricum*."

Studies of submarine cores from the continental shelf of the northeastern United States were published by Phleger (1939, 1942). There are several faunas in these cores which contained displaced benthonic Foraminifera, and the displacement was not realized at the time those studies were published. Hamilton (1953, p. 216) has recognized displaced faunas near a flat-topped seamount in the central Pacific basin. Displaced faunas have been described from the San Diego Trough, off Southern California (Phleger, 1951a).

The possible significance of displacement in sedimentation in the deep sea has been summarized by Phleger *et al.* (1953, p. 120) based on their studies of cores from the North Atlantic :

" The widespread occurrence of displaced faunas may be of considerable importance to the deposition of sediment in the North Atlantic. The displaced faunas appear to be located near areas of considerable relief. Data from these cores and from elsewhere suggest that displaced faunas cover only a small percentage of an ocean basin, even though they may have considerable areal extent. It appears reasonable to assume that sediment being displaced to the deep ocean will carry an assortment of sediment from clay through sand sizes. It is expected that there will be differential sorting of these sizes as the sediment is moved downslope and gradually loses velocity, with the sand sizes deposited first, nearest the source. Tests of Foraminifera may be considered as sand particles in their reaction to processes of sediment transportation and deposition so that any Foraminifera which are contained in the sediment will be deposited along with the sand-size material. It is expected that they will be deposited along with grains of sand smaller than the tests themselves since they have a relatively low density per unit volume. The fine silt and clay sizes of the material being displaced will be carried beyond the coarser material and deposited. This fine-grained sediment is expected to carry no tests of Foraminifera since they have been deposited with the sand.

" It appears probable that some of the fine-grained sediment in the deep North Atlantic, far from sources of supply, is the fine fraction of displaced sediment. A considerable percentage of sediment in these deep basins thus may of be terrigenous origin. Deposition of the fine sediment by this mechanism should have no effect on the stratigraphic sequence of planktonic Foraminifera in these sediments. Interpretations of chronology based upon planktonic populations in cores collected from such areas are expected to be as valid as those from any area of the ocean."

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ON GRAVITY WAVES IN THE ATMOSPHERE

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(Manuscript received 9 November 1953)

ABSTRACT

Seven times in a year's continuous observations, marked oscillations with periods from 5 to 15 minutes were simultaneously recorded on a barograph and a damped anemometer located at La Jolla, California. The oscillations often followed a reversal of the land- and sea-breeze regime, and they were sometimes preceded by a pressure pulse. Perturbations of pressure (p) and wind speed (v) attain double amplitudes up to several millibars and several meters per second, respectively, with maximum pressure occurring at the time of maximum "orbital" wind. This suggests propagating gravity waves in the atmosphere. Their velocity (C) can be inferred from the La Jolla records according to the impedance relationship, $p = \rho v C$; the computed arrival time at Point Loma, 11 miles to the south, agrees with the recorded arrival. Phase velocities are of the order of 10 m/s and greatly exceed ambient winds. Wavelengths range from 4 to 10 kilometers. A slight effect on sea level is apparent. Under steady meteorological conditions, there is good coherence for at least four wavelengths in the direction of propagation, but less coherence at right angles to this direction. The wave crests appear to be oriented normal to the wind shear between the upper and lower winds. The observed wave velocity is of the order given by the shallow "water" theory, *i.e.*, $(gh\,\Delta \ln \theta)^{\frac{1}{2}}$, where h is the elevation of the inversion layer, and $\Delta \ln \theta$ is the logarithmic change in potential temperature across this layer. The observed period is not inconsistent with the period $2\pi/s$ of the fundamental mode of the least dispersive (longest) "trapped" waves, where $s^2 = g\,d(\ln \theta)/dz$ is a measure of the stability *above* the inversion layer.

. Introduction

Since 1950, continuous recordings of ocean waves vith periods of 10 to 20 min have been made at the cripps Institution of Oceanography in La Jolla. n early 1952, simultaneous recordings of atmospheric ressure and of appropriately damped wind-speed nd -direction were added to the installation in the ope of finding some connection between the oceanic nd atmospheric disturbances. It has developed that his *combination* of pressure records with suitably lamped wind records offers a powerful method for nvestigating atmospheric gravity waves. The origin f the long ocean waves remains in doubt, but we eem to have learned something about waves some 000 ft above the sea surface.

. Instruments

Wind direction and speed.—A standard Friez *erovane* is located in a well exposed position at the d of Scripps' pier, about 30 ft above mean sea level nd 1000 ft from shore. The aerovane actuates a near servo unit, which drives a Selsyn. The Selsyn perates a linear potentiometer, which constitutes one-half of a balanced bridge. The propeller drives a d.c. generator. Both the bridge output and generator output are fed into integrating circuits with time constants compatible with the long-period ocean waves (see table 1).

Microbarograph.—The sensing unit is located in a flush pit at the shore end of the pier. It consists of a conventional aneroid cell, with the tension countering the vacuum provided by a suspended weight with a natural period of oscillation of something less than a second. The strain-gauge element is a balanced bridge whose output is recorded directly.

Barovariograph.—This is located at Point Loma, 11 mi south of Scripps (fig. 8), at an elevation of 350 ft above sea level. It is operated by the Exploratory Studies Section of the Navy Electronics Laboratory, to whom the writers are indebted for use of their records. The instrument is essentially a low-frequency microphone which has a "front" leak and a "back" leak into its two chambers. The response range is roughly from 12 sec to 6 min.

TABLE 1. Instrumental time constants, and resulting phase lags and amplitude reductions for waves of stated periods.

	Time const. (sec)	Phase lag (sec)			Amplitude factor		
		5 min	10 min	15 min	5 min	10 min	15 min
Wind direction	180	63	103	128	0.26	0.47	0.62
Wind speed	50	39	45	46	0.69	0.89	0.95

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[1] Navy Electronics Laboratory Professional Contribution No. 7.

[2] Contribution from the Scripps Institution of Oceanography, ew Series No. 720. This work has been supported by the Office Naval Research.

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The wind and pressure measurements at Scripps are recorded on a multi-channel Leeds and Northrup *Speedomax* together with air and sea temperature, and measurements of water level from the "tsunami recorders" (Munk *et al*, 1948) at Scripps and at Oceanside, 25 mi to the north-northwest of La Jolla. The recorder prints a dot for each of these measurements once every 38.7 sec (for example, fig. 1). This intermittent type of recording has been used to advantage in the analysis, for it provides a much more precise time scale than can be obtained under similar circumstances by a continuous record.

3. Observations

During the seven days listed in table 2, oscillations were recorded at the La Jolla installation. The observed data are summarized in lines 1–17. The observed periods (T) and frequencies ($\sigma = 2\pi/T$) are given in lines 7 and 8. Figs. 1–3 show the original records for the three best cases. Figs. 4 and 5 show the corresponding pilot-balloon and radiosonde data taken in San Diego, about 11 mi southeast of La Jolla. The definitions of the various velocity vectors are given in the legend to fig. 8.

Weather conditions.—In all cases, the oscillations occurred when there was a large temperature inversion over the area. The amount ($\Delta\theta$) and the elevations of the bottom (h) and top (h') of the temperature inversion are listed in lines 12–14 of table 2. This inversion was always quite low. In southern California such an inversion is often accompanied by fog or very low stratus (line 3). These conditions are usually found in the late summer or fall, when the southern California area is under the influence of a well-developed Pacific high-pressure system.

The ambient surface wind V (line 4) was very light, and the land- and sea-breeze sequence was usually well developed The oscillations often occurred after some directional change in the established surface flow.

The orbital winds.—From the original recordings of wind speed and direction, oscillating wind vectors were constructed, allowance having been made for the attenuations and phase lags introduced by the two instruments. The wind field was then resolved into a mean wind vector V and an orbital wind vector v (fig. 6). The construction was performed for each individual oscillation, or for two or three oscillations combined. Representative averages are given in line 4 for the mean winds, and in line 5 for the orbital winds. The ambiguity in orbital direction by 180 deg is discussed in the following section. It will be seen that in most cases the magnitude of the orbital wind

TABLE 2. Summary of observed and computed data for the seven occasions between April 1952 and May 1953 when marked oscillations occurred. Wave directions indicate directions *from* which waves are coming, in conformance with wind convention.

1. Date	4 April	27 July	4 Aug.	4 Sept.	2 Oct.	16 Oct.	16 Oct.	12 May
2. Time (PST)	1100 to 1300	0200 to 0310	1140 to 1400	0430 to 0530	0652 to 0710	0400 to 0600	0620 to 0720	0000 to 0040
3. Weather	Fog	Clear	Fog	Clear	Fog	Fog	Fog	Clear
Tsunami recorder data								
4. V (m/s and dir.)	1.4/NNW	0.9/NE	2.9/W	2.2/N	1.2/WSW	0.8/NNE	0.9/NW	0.7/ENE
5. $2\ \Delta v$ (m/s and deg)	2.0/200	2.6/78	2.3/175	1.0/318	6.4/240	2.8/208	1.8/282	3.2/280
6. $2\ \Delta p$ (mb)	0.28	0.36	0.36	0.14	0.86	0.40	0.26	0.26
7. T (min)	14.0	7.5	6.5	5.5	8.5	7.5	7.5	11.0
8. σ (sec^{-1})	0.0075	0.014	0.016	0.019	0.012	0.014	0.014	0.0095
San Diego pibal data								
9. Time (PST)	1300	0100	0700	0100	—	0100	0700	0700
10. V' (m/s and dir.)	1.4/SW	4.5/NNW	2.7/NW	7.6/NNW	—	1.8/W	5.0/ESE	3.6/N
San Diego raob data								
11. Time (PST)	0700 and 1900	1900* and 0700	0700 and 1900	1900* and 0700	1900*	0700 and 1900	0700 and 1900	1900 and 0700
12. h (m)	170	170	300	260	210	180	180	100
13. h' (m)	600	670	1190	740	1000	670	670	400
14. $\Delta\theta$ (deg C)	15.0	14.0	20.0	10.5	11.5	17.5	17.5	6.0
15. s_1 (sec^{-1})	0.0086	0.0	0.0077	0.0	—	0.017	0.017	—
16. s_2 (sec^{-1})	0.037	0.030	0.028	0.031	0.024	0.035	0.035	0.025
17. s_3 (sec^{-1})	0.0086	0.010	0.0077	0.014	0.0056	0.0080	0.0080	0.0096
Computed values								
18. C_i (m/s and deg)	12/200	12/78	13/175	12/318	11/240	12/268	12/282	6.7/280
19. $\bar{U}$ (m/s)	−0.6	+0.5	−0.6	+2.6	—	+0.07	+0.12	−0.09
20. L (km)	9.6	5.0	4.9	4.8	5.6	5.4	5.4	4.4
21. Two layers, L (km)	10.0	5.4	5.9	4.2	6.8	5.4	5.4	4.0
22. Three layers, L_I (km)	8.4	3.8	4.9	3.8	5.8	4.5	4.5	3.8
23. L_{II} (km)	2.8	1.2	1.7	1.2	1.9	1.5	1.5	1.3

* Preceding day.

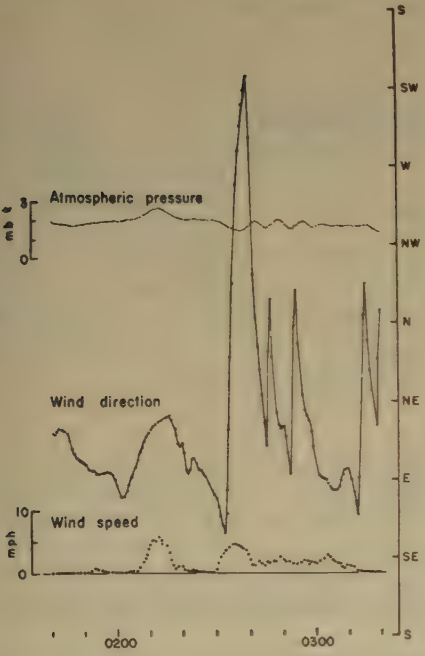

FIG. 1. *Speedomax* record for 27 July 1952. Scales for wind peed and direction apply to steady-state conditions; for short-eriod oscillations, allowance must be made for instrumental hase lag and attenuation (table 1).

ctually exceeded that of the mean wind, so that the bserved motion near the ground was largely the esult (as will be shown) of internal wave activity. his corresponds to conditions found at the bottom f shallow stratified lakes.

An inspection of fig. 6 shows that the wind speed vill reach maximum values for both directional extremes whenever the orbital motion is approximately at right angles to the mean wind vector, or when the mean wind vector is small. This accounts for the "double frequency" in the wind speed record (see fig. 3, 0400–0500 PST). If the orbital motion is approximately along the mean vector, the fundamental frequencies of wind speed and direction are the same. The relative frequencies and amplitudes of the two traces give, therefore, a quick indication of the orbital direction. It is clear that for simple harmonic motion both speed and direction records will depart in general from a sinusoidal form, and we have allowed for this as well as possible in correcting for instrumental characteristics. For very weak winds the instrumental threshold becomes an appreciable factor, and the measured values tend to be low and unreliable.

Phase relation between wind and pressure oscillations.—Fig. 7 shows the results of a cross-correlation between pressure and wind direction. The analysis was made for the exceptionally well defined oscillations occurring between 1223 and 1320 on 4 August (fig. 2). Values were read for successively printed points of pressure and direction, and the two traces were correlated. Thereupon the direction trace was displaced in time relative to the pressure trace by one point (38.7 sec) and a new correlation performed, *etc.* If the maxima in direction and pressure had occurred simultaneously, the maximum correlation should occur for the instrumental time lag of about 80 sec for 6½-min waves (table 1). Actually the optimum correlation occurs for about 93 sec. Thus, maximum pressure occurs at the time of maximum orbital wind. The orbital wind direction at the time of maximum pressure is given in line 5 of table 2.

Phase velocity and wave length.—The correlation between pressure and orbital motion strongly indicates that we are dealing with propagating waves (rather

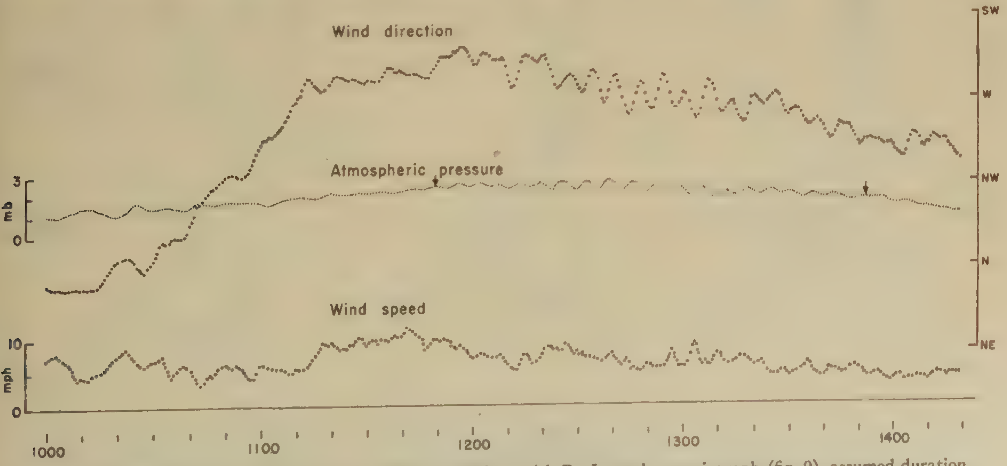

FIG. 2. *Speedomax* record for 4 August 1952. For comparison with Pt. Loma barovariograph (fig. 9), assumed duration of pressure disturbance is indicated by arrows.

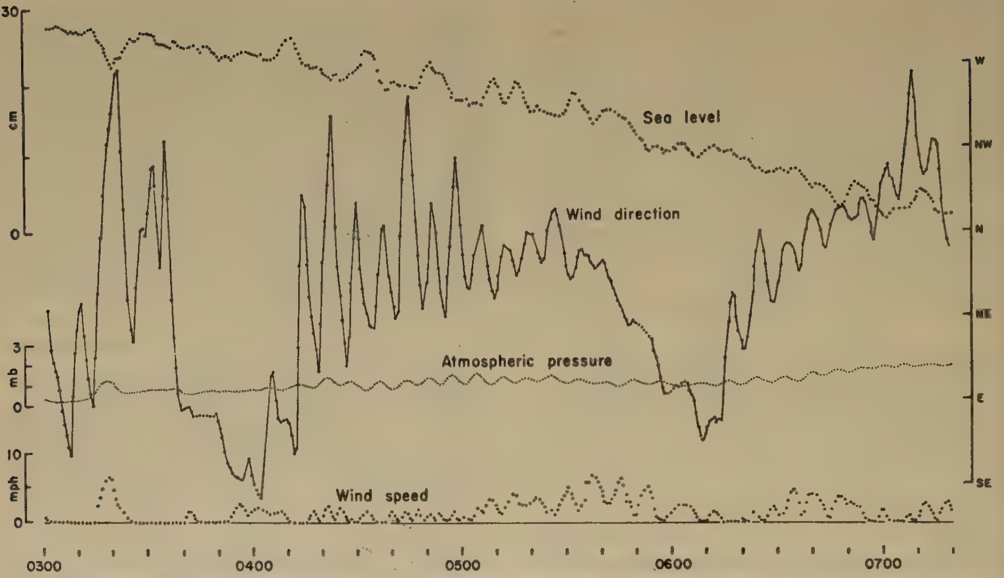

FIG. 3. *Speedomax* record for 16 October 1952. La Jolla sea-level record (cm) is included to show correlation with initial pressure pulse; remainder of record shows little correlation; sea level is recorded on La Jolla tsunami recorder. Scale appropriate to 9-min oscillations is shown on left; corresponding instrumental phase lag is 2 min.

than drifting convection cells, see section 4, below). If this is the case, a knowledge of both pressure and orbital motion permits us to compute phase velocity C_i. This velocity is in the plane of orbital motion; its direction is that of the orbital velocity v at the time of positive pressure perturbation[3] p, and its magnitude

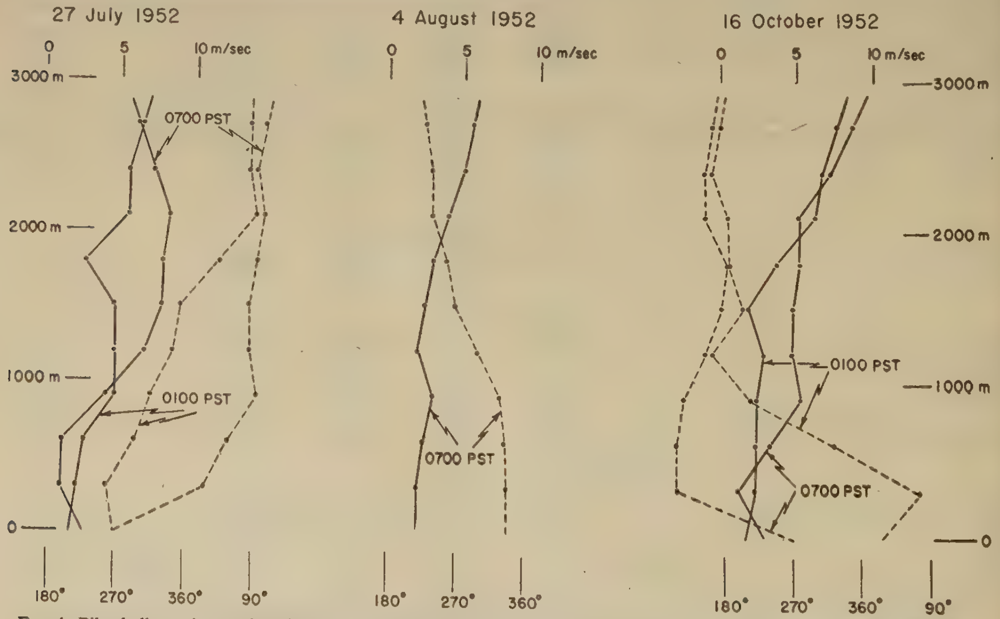

FIG. 4. Pilot-balloon observations for three days during which records in figs. 1–3 were taken. Solid lines connect measured values of wind speed. Dashed lines connect measured values of wind direction.

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[3] This is true not only for the theoretical models under consideration in section 5, below, but for gravity waves in general. In ocean waves, for example, maximum pressure and orbital motion in the direction of propagation both occur beneath the crest.

s given by the "impedance relationship," $C_i = p/\rho v$. Hence

$$C_i = (p/\rho v)\, v_1, \tag{1}$$

where v_1 is a unit vector in the direction of v during positive p, and $v = v \cdot v_1$. This relationship is familiar n acoustics as a means of inferring orbital velocity rom measured pressure and wave velocity.

Equation (1) follows from the horizontal equation of motion,

$$\rho\, \partial v/\partial t + \rho V \cdot \Delta v = -\Delta p,$$

where V is the mean drift, and v is the perturbation velocity. For solutions of the type $v, p \propto \exp i(m \cdot r - \sigma t)$, this gives

$$\rho \nu v = p m, \tag{2}$$

where

$$\nu = \sigma - m \cdot V \tag{3}$$

can be seen to be the frequency noted by an observer drifting with velocity V, whereas σ is the frequency at a fixed point.[4] The perturbations are therefore transmitted in the direction of v_1 with a speed $\nu/m = p/\rho v$ relative to the drifting observer. Hence C_i is the *relative* phase velocity. According to (1) and (2), C_i is in the direction of m, hence perpendicular to the wave crests. In the presence of a mean wind, the travel time of a long crest between two points will be shortened or lengthened according to whether the wind blows in the direction of wave propagation or opposite, but the travel time will not be affected by a wind blowing along the crests. The absolute phase velocity C relative to the ground is therefore a vector in the direction of C_i (normal to the crests) with magnitude $C = C_i + U$, where U is the projection of V on C_i. If the surface winds differ from the winds aloft, U must be replaced by an appropriately weighted average $\bar{U}$ [see (15)]; hence,

$$C = C_i + \bar{U}. \tag{4}$$

The travel time for a coherent crest between two recorders is then $\Delta x/C$, where Δx is the projection on C_i (and, of course, on C) of the distance between the recorders. The wave length is $L = CT$, where T is the period recorded by fixed instruments.

Numerical values for C_i, $\bar{U}$ and L are given in lines 18–20 of table 2. The values for wave speed and direction can be independently checked by comparison between computed and recorded arrivals at Point Loma (fig. 9). In most cases the waves travelled at nearly a right angle to a line connecting the recorders, and the calculation depends too critically on the measured orbital direction to provide a critical check on the velocity. However, on 4 August the wave direction was nearly parallel to the line between the recorders (fig. 8). The arrivals of the disturbance at the two stations (marked by arrows on figs. 2 and 9) correspond to a travel time of 23.5 min, compared to a computed value of 24.2 min. In this computation, phase velocity was used rather than group velocity, the two being nearly equal for the long waves here under consideration (see section 5, below).

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[4] Strictly speaking, this applies only to one-directional propagation; but the results are only slightly modified if the "beam width" is narrow.

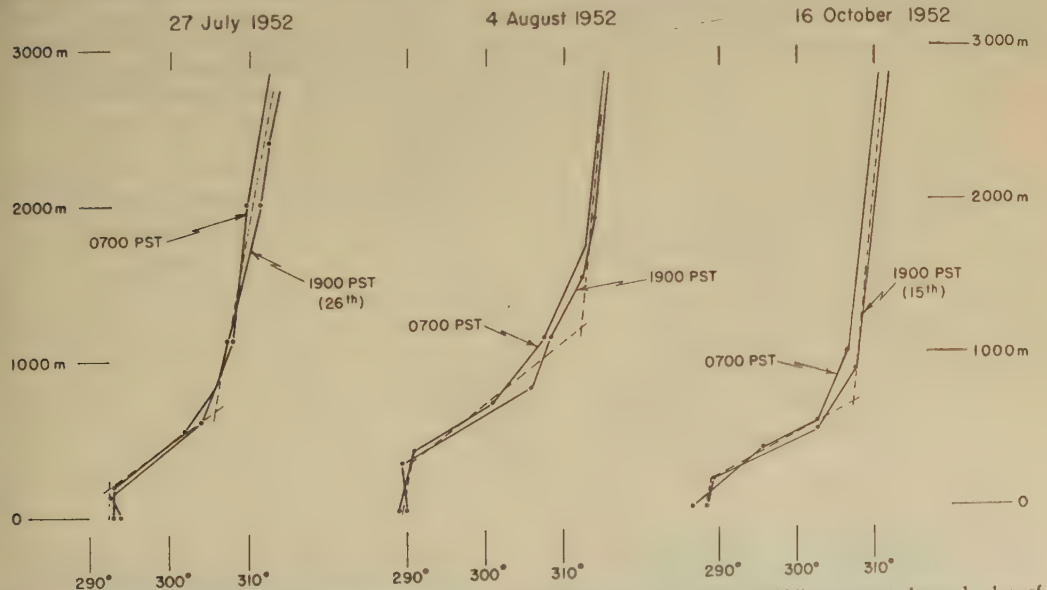

FIG. 5. Radiosonde observations for three days during which records in figs. 1–3 were taken. Solid lines connect observed values of potential temperature in deg K. Dashed lines indicate relationship assumed in theoretical models.

Coherence.—A comparison of the records in figs. 2 and 9 reveals good coherence at the two stations, which are separated by four wavelengths. Nineteen principal crests are identifiable. On days when the wave direction was more nearly normal to the line between the stations, the coherence was considerably poorer. The waves would therefore appear to be short-crested. It should also be noted that on 4 August the direction of propagation remained nearly uniform during the entire disturbance. On other occasions the direction of propagation changed rather rapidly, and the coherence along any fixed direction was not as good.*

Effect on sea level.—Correlation between pressure and sea-level oscillations is found at times. In fig. 3, the initial pressure pulse is clearly accompanied by a depression in sea level. The best correlation for the seven days under consideration is shown in fig. 11. In most cases, the correlation is not convincing. One factor might be that the tsunami recorder is peaked at a period of 45 min and is therefore relatively insensitive to the observed shorter periods.

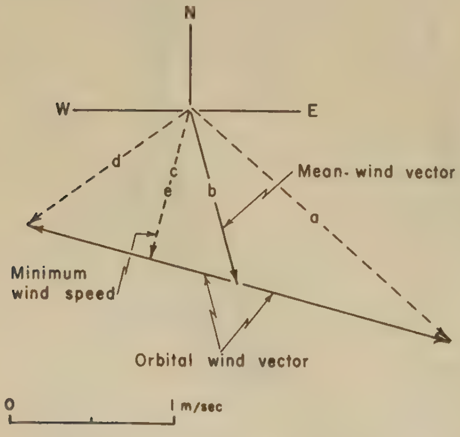

FIG. 6. Dashed arrows indicate wind vectors (pointing downwind) at five successive times, a, b, . . . e, during interval 0501–0505 PST 16 October 1952. Construction is based on wind speed and direction records shown in fig. 3, allowing for instrumental characteristics. Oscillating wind vector has been resolved into mean vector, 1.1 m/s and 345 deg, and an orbital vector, 1.4 m/s and 285 and 105 deg.

4. Discussion

Waves or drifting convection cells.—The evidence favors waves. In the first place, the recorded travel time between La Jolla and Point Loma was of the order of 10 per cent of the time required for any disturbance drifting with the mean wind. Secondly, orbital velocity and pressure oscillations were in phase (see fig. 7) as they are in propagating waves, and not 90 deg out of phase as they are in convection cells. Thirdly, if we interpret the recorded fluctuations as being due to convection cells, their horizontal dimensions would be many times larger than their vertical dimension, taken as the elevation of the inversion base. This does not seem likely; convection theory indicates the proper ratio to be about 2:1. Finally, the occurrence of oscillations seems to be characteristic of great overall stability in the lower atmosphere.

It therefore seems reasonable to assume that the fluctuations were caused by some type of progressive waves. Phase velocities computed on the basis of this assumption [equation (1)] are in accordance with those observed.

Wave direction.—It was first stated by Wegener in 1908, and later supported by Trey's observations, that waves associated with billow clouds "are perpendicular to the wind shear" (Haurwitz, 1947). For the waves here under consideration, the average deviation from this law is 23 deg, compared to 45 deg for a random distribution in direction. In half the cases the waves travelled roughly in the direction $V' - V$, and in the other half in the direction $V - V'$. In this comparison it must be remembered that the upper-wind observations were usually taken several hours before or after the oscillations occurred. Furthermore, by their very nature, pilot-balloon soundings smooth out and even erase abrupt discontinuities, making the choice of "upper" and "lower" winds quite arbitrary.

Somewhat more information can be gained by considering in detail the interval from 1100–1300,

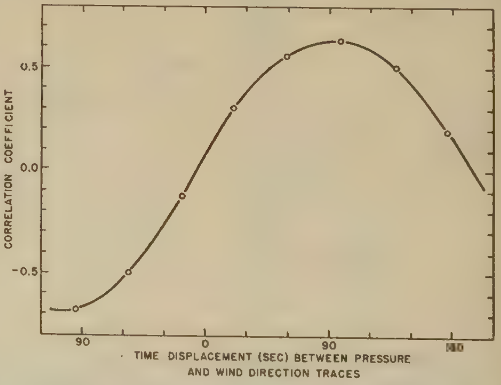

FIG. 7. Correlation between pressure and wind direction, 1223–1320 PST 4 August (fig. 2), for stated time displacements between two traces. Computed points are shown by circles.

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* *Note added in proof.* On 15 May 1954, pronounced oscillations commenced at 0200 PST at San Diego and about an hour earlier at Los Angeles. Five stations in the San Diego area indicated propagation to be from WSW. If the disturbance is assumed to have been propagated with a group velocity appropriate to the observed frequency, the disturbance was placed roughly 575 mi out to sea. This was not inconsistent with the location of a secondary low center. The inversion over southern California was marked. The simultaneous occurrence of inversion conditions and a low this far south is unusual.

The situation was similar to the one on 2 October 1952. Upon re-examination, we find that a disturbance did arrive in Los Angeles about 4 hr after the arrival in San Diego. There may be a connection with a tropical storm off the coast of Mexico several days earlier.

In other cases, the cause of the disturbance appears to be local.

4 August 1952, when the mean surface wind veered from WSW to WNW (fig. 10). The only available information concerning the upper wind is the 0700 pilot-balloon sounding at San Diego, giving 2.7 m/sec from NW (lines 9 and 10, table 2). However, it is known that reversal in the land- and sea-breeze sequence, or the onset of katabatic winds, often commences at the surface with winds at gradient level remaining at least temporarily unaffected. We therefore assume a steady upper-wind vector whose tip lies in the general area near *P*. As the surface wind veers, the shear vector must change accordingly, and by the above hypothesis the waves should travel along the line between the tip of the surface wind vector and *P*. It is seen that the observed wave direction does, in fact, vary roughly in the required fashion.

A similar analysis for the record of 16 October implies a weak upper wind from WNW at about 0500 PST, and a somewhat stronger wind from ENE

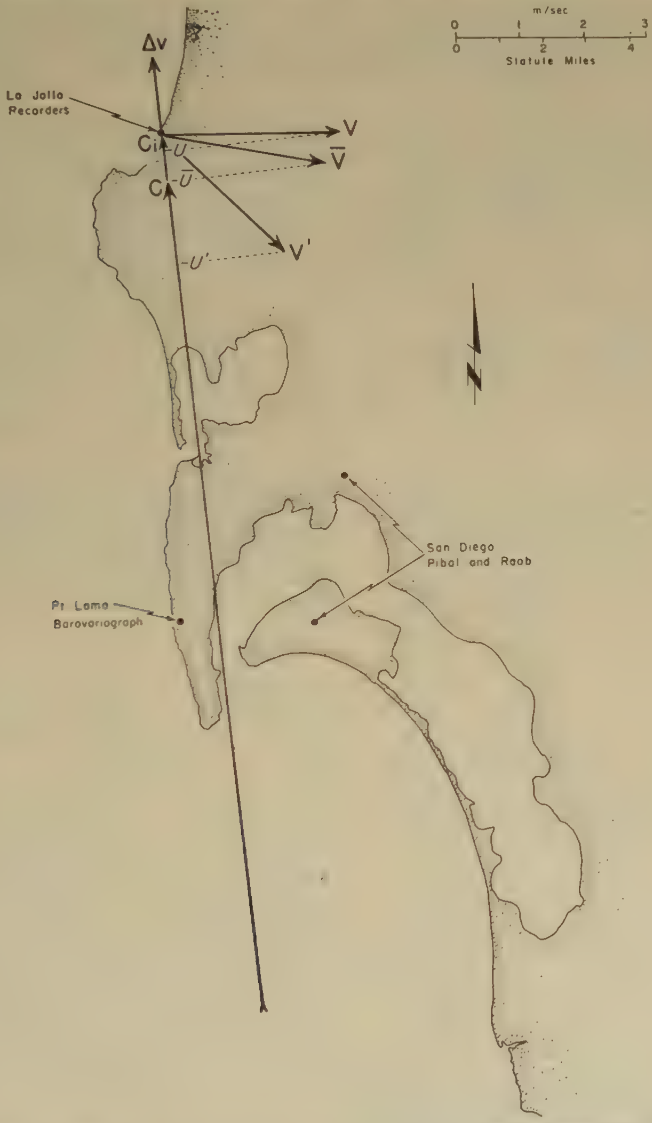

FIG. 8. Vector diagram for 4 August, showing mean surface wind *V*, upper wind *V′*, weighted mean wind $\bar{V}$ [equation (15)], surface orbital wind Δv at time of maximum pressure, and "impedance wave velocity" C_i. Scalars *U*, *U′* and $\bar{U}$ refer to projections on $+C_i$ of surface, upper and mean winds. For case shown, these quantities are negative. Wave velcity *C* relative to ground is in direction of C_i and has magnitude $C_i + \bar{U}$. All arrows point downwind or "down wave." They are centered on underlying map on site of La Jolla recorders (*V′* is measured in San Diego). Location of the barovariogram at Point Loma is indicated.

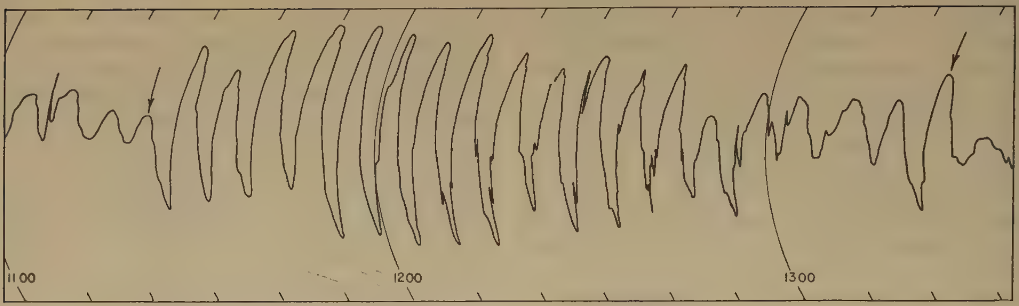

FIG. 9. Barovariograph record for 4 August 1952. For comparison with La Jolla record (fig. 2), assumed duration of disturbance is indicated by arrows. Full scale is approximately 0.5 mb.

after 0630. The San Diego pilot-balloon data show a strengthening and shift from W to ESE between 0100 and 0700 PST (lines 9 and 10, table 2).

On the basis of the above evidence, it can be said that the observations are not inconsistent with the assumption that the waves travel parallel to the wind shear. As seen from line 18, table 2, no particular direction is dominant, and the orientation of the coastline seems immaterial.

Wave velocity.—In the theory of billow clouds, it is often assumed that wave and wind speed are of the same order. Here we find $C \approx 10\ \bar{U}$ (lines 18 and 19, table 2).

5. Comparison with theory

Even a largely descriptive account, such as this one, would be incomplete without some comparison with theory. The theory of internal waves is well developed, due largely to the efforts of Helmholtz, Hoiland, Fjeldstad and Taylor. However, none of the published solutions is quite applicable to the present case. By following the general scheme in the developments by Fjeldstad (1933) and Queney (1946), we can give an abbreviated account.

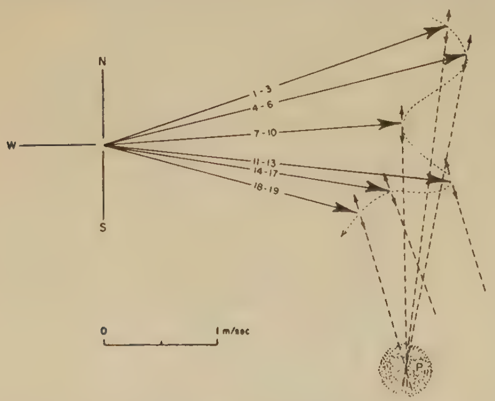

FIG. 10. Arrows drawn from origin point downwind in direction of mean surface wind during interval 1100–1300 PST 4 August 1952. Two-pointed arrows at end of wind vectors give orientation, but not strength, of orbital winds. Construction follows method shown in fig. 6. Dashed lines are extensions of orbital vectors in direction of wave propagation. Waves occurring during interval were numbered 1, 2, ... 20, and three or four successive waves combined into averages, as designated. Most of dashed lines converge in vicinity of *P*.

Perturbation equations.—The perturbation equations of motion, continuity and of the first law of thermodynamics for isentropic change are

$$\dot{\boldsymbol{v}} + (1/\rho_0)\,\nabla p = -\,(\rho/\rho_0)\boldsymbol{g}, \qquad (3, 4, 5)$$

$$(1/\rho_0)(\dot{\rho} + w\,d\rho_0/dz) = -\,\nabla\cdot\boldsymbol{v}, \qquad (6)$$

and

$$\dot{\rho} + w(d\rho_0/dz) = c^{-2}(\dot{p} - \rho_0 g w), \qquad (7)$$

where $p_0(z)$ and $\rho_0(z)$ are the unperturbed distributions of pressure and density, c is sound velocity, and $(\dot{\ })$ designates the substantial derivative following the unperturbed flow (assumed not to vary continuously). The remaining notation is conventional. Eliminating ρ and using the relationship $s^2/g = 2S - g/c^2$, where

$$s^2 = g\,d(\ln\theta)/dz \text{ and } S = -\tfrac{1}{2}\,d(\ln\rho_0)/dz, \qquad (8)$$

we obtain

$$\ddot{w} = -\frac{1}{\rho_0}\left(\frac{\partial}{\partial z} + \frac{g}{c^2}\right)\dot{p} - s^2 w, \qquad (5a)$$

and

$$\nabla\cdot\boldsymbol{v} = -\,(1/\rho_0 c^2)\dot{p} + (g/c^2)w. \qquad (6a)$$

Equations (3), (4), (5a) and (6a) are linear and homogeneous in the four dependent variables $\rho_0^{\frac{1}{2}}\boldsymbol{v}$ and $\rho_0^{-\frac{1}{2}}p$ (Queney, 1946). Furthermore, this system of equations has constant coefficients, provided s, S and U are constants over specified height intervals.[5] Here U designates the component of the (unperturbed) drift in the direction of wave propagation. Without loss in generality, we can take the x-axis in this direction and assume solutions of the form exp i $(mx \pm nz - \sigma t)$. This leads to the dispersion equation,

$$\nu n^2 = m^2(s^2 - \nu^2) - \nu^2 S^2 + \nu^4 c^{-2}. \qquad (9)$$

---

[5] The case of a continuous shear has been examined by Sekera (1948); but since we observe $U \ll C$ in all cases, this extension is not critical here.

For the observed frequencies and wavelengths, this reduces to

$$\nu^2 n^2 = m^2(s^2 - \nu^2). \qquad (9a)$$

Here

$$\nu = \sigma - Um \qquad (10)$$

is the frequency noted by an observer drifting with the wind.

Boundary conditions.—Fig. 5 shows that the measured profiles of potential temperature can be represented by:

1. a lower mixed layer, from $z = 0$ to $z = h$;
2. a stable (inversion) layer, from $z = h$ to $z = h'$;
3. a layer with two-thirds to three-fourths the dry-adiabatic lapse rate, above $z = h'$.

Mean values of h, h', s_1, s_2 and s_3 are given in table 2.

We shall derive solutions for two special cases: (a) a simplified two-layer model with a wind and density discontinuity at the boundary $h'' = \frac{1}{2}(h + h')$ midway in the inversion layer, and with s_1, U, and s_3, U' referring to the lower and upper layers, and (b) a continuous three-layer model with no shear in the mean wind field. In the two-layer model, U and U' refer again to the projection of the wind vectors along the direction of propagation. The crosswind components are not excluded in the derivation, but their existence does not affect the solution. In the three-layer model, we have assumed

$$\nu_1 = \nu_2 = \nu_3 = \bar{\nu} = \sigma - \bar{U}m, \qquad (11)$$

where $\bar{U}$ is the projection of a weighted mean wind (line 19, table 2) in the direction of wave propagation.

Equations (9) and (10) hold in each of the layers, but in the general case S_k, s_k, ν_k, U_k and n_k ($k = 1, 2, 3$) are different in each of the layers, whereas m and σ are the same throughout. The solutions for the different layers are patched together by requiring w and

$$d(p_0 + p)/dt = \dot{p} + w\, dp_0/dz \qquad (12)$$

to be continuous across the interfaces.[6] With the additional boundary conditions

$$w_1 = 0 \text{ at } z = 0 \text{ and } w_3 \neq \infty \text{ at } z = \infty, \qquad (13)$$

and the relationship (5a) between w and p, we can evaluate the six constants c_k and d_k in

$$w_k = e^{S_k z}(c_k e^{i n_k z} + d_k e^{-i n_k z})\, e^{i(mx - \sigma t)}.$$

Solutions.—The derivation of the solutions is cumbersome and uninteresting. For the two-layer model, the result is a slightly generalized Helmholtz equation,

$$\frac{\bar{\nu}}{m} = \frac{\sigma}{m} - \bar{U}$$
$$= \pm\left[\frac{g\,\Delta\theta}{A_1 + A_3} - \frac{A_1 A_3}{(A_1 + A_\beta)^2}(U' - U)^2\right]^{\frac{1}{2}}, \qquad (14)$$

where

$$\bar{U} = (A_1 U + A_3 U')/(A_1 + A_3) \qquad (15)$$

is a weighted average wind, $\Delta\theta = (\theta_3)_{z=h''} - (\theta_1)_{z=h''}$

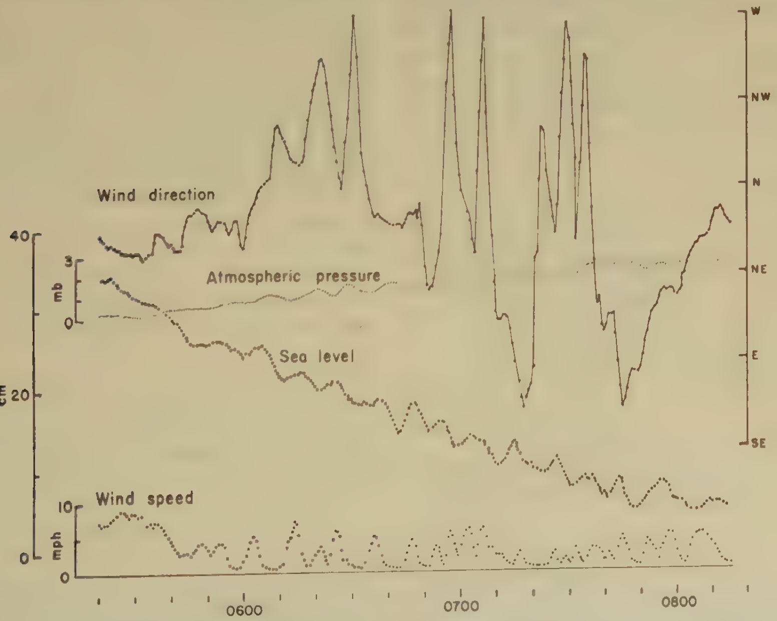

FIG. 11. *Speedomax* record for 2 October 1952, including sea level (cm) as recorded on La Jolla tsunami recorder. Sea-level scale is appropriate to oscillations of 9-min period. Corresponding instrumental phase lag is 2 min.

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[6] For the three-layer model, $\rho_0(z)$, and hence $w\, dp_0/dz$, is already continuous across the interfaces.

is the discontinuous change in potential temperature across the boundary, $A_1 = (\theta_1)_{z=h''}\ \gamma_1 \coth\ (\gamma_1 h'')$, and $A_3 = (\theta_3)_{z=h''}\ \gamma_3$, with γ_1 and γ_3 denoting $-in_1$ and $-in_3$. For the three-layer case,

$$n_2 \cot n_2(h'-h) = \frac{(S_3-S_2-\gamma_3)(S_1-S_2+\gamma_1 \coth \gamma_1 h)+n_2^2}{S_1-S_3+\gamma_3+\gamma_1 \coth \gamma_1 h}. \tag{16}$$

The terms S_1, S_2 and S_3 can be neglected, provided the unperturbed density changes a small fraction of its mean value in the part of the atmosphere affected by wave motion. Across a thin inversion layer, $\Delta(\ln \theta)$ and $n_2(h' - h)$ are small numbers. The above equation then yields a fundamental mode,

$$C^2 = (g\,\Delta\theta)/(A_1 + A_3), \tag{16a}$$

in agreement with the two-layer formula (14) for $U = U' = \bar{U}$. The simplest case is that of a shallow layer, $\gamma_1 h \ll 1$, and $\gamma_1 \approx \gamma_3$, as observed. Then,

$$C^2 = gh\,\Delta(\ln \theta). \tag{16b}$$

The two solutions (14) and (16) are plotted in fig. 12, with the here unimportant wind terms omitted. For the case under consideration, we may also neglect the S's and set $s_1 = s_3$. Consider any point on the curves $\sigma(m)$. The slope of the line from the origin through this point is the phase velocity σ/m, and the tangent $d\sigma/dm$ is the group velocity.

For all frequencies between (s_1, s_3) and s_2, the vertical wave numbers n_1 and n_3 are imaginary, and n_2 is real [equation (9a)]. Hence the assumed solutions $\exp i(mx \pm nz - \sigma t)$ are vertically trigonometric, or *cellular*, in the inversion layer, and hyperbolic in the lower and upper layers (fig. 13). This means that wave motion essentially vanishes a distance $1/\gamma_3$ above the inversion layer, *i.e.*, that the wave energy is *trapped* in the lower atmosphere.

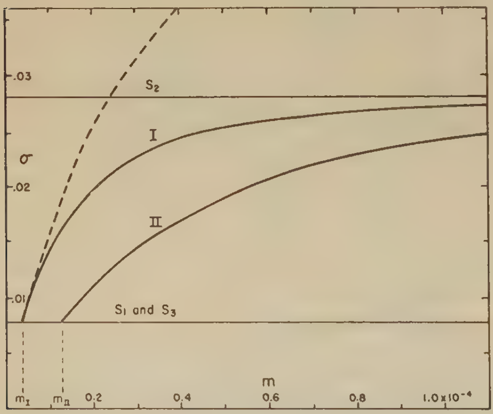

FIG. 12. Plot of frequency σ (sec^{-1}) as function of wave number m (cm^{-1}), pertaining to conditions on 4 August. For frequencies less than s_1 or s_3, σ is complex. Solid lines refer to fundamental (I) and second mode (II) of three-layer model (16). Dashed line refers to two-layer model (14).

There are no solutions for frequencies larger than s_2, other than sound waves. The two-layer case may be considered a special case of the three-layer model in which the middle (inversion) layer has collapsed, so that $s_2 \to \infty$, and σ is unbounded for large m.

For frequencies less than s_3, the upper wave number n_3 is real, and the cellular solution extends to infinite height. Both solutions yield complex frequencies, and hence the wave amplitudes must vary with time. The physical interpretation is that these *untrapped* modes radiate energy into the upper atmosphere. In analogy with the "potential trap" problem in quantum mechanics (*e.g.*, Rasetti, 1936, pp. 100–114; Condon and Morse, 1929, pp. 228–231), we may expect continuous spectra (noise) for this range of frequencies in addition to the discrete spectral lines $\sigma_I(m)$, $\sigma_{II}(m)$, . . . *etc.* Here it may turn out that solutions are essentially modified if s is not constant above a certain height, as here assumed, but only approaches a constant asymptotically.

A proper treatment of these problems that arise when $\sigma \ll s_3$ involves the solution to the appropriate initial value problem. We have not attempted this here. In all events, for waves generated at some distance by a disturbance in the lower layers, those most likely to persist at the lower levels are the trapped modes. These include the fundamental and various overtones (such as curves I and II in figs. 12 and 13), and for each of these modes all frequencies between s_3 and s_2 are possible. Which of these modes and frequencies will be the most prominent depends on three considerations: (1) how these oscillations are initially excited, (2) how they are transmitted, and (3) how they are recorded.

If the initial disturbance is so large that its spectrum contains only wave numbers smaller than m_I (wavelength larger than $2\pi/m_I$), no trapped modes at all will be excited (fig. 12). If the disturbance spectrum

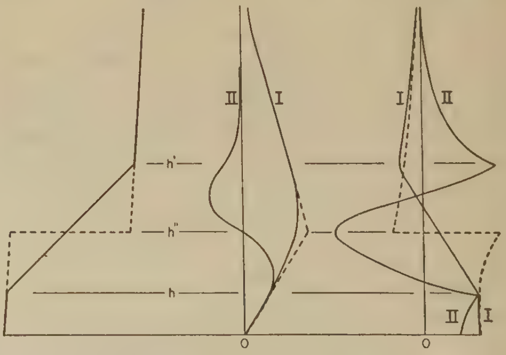

FIG. 13. Left: assumed distribution of potential temperature for two-layer (dashed) and three-layer (solid) models. Middle: corresponding distributions of vertical velocity, including two gravest modes for three-layer case. Right: corresponding distributions of pressure or horizontal velocity.

extends just past m_{I}, waves of wave number m_{I} and frequency $\sigma(m_{\text{I}}) = s_3$ of the fundamental mode are excited. If it extends up to, but not including, m_{II}, the oscillation is still limited to the fundamental mode, but it now consists of a "wave packet" containing all wave numbers between m_{I} and m_{II} and the corresponding frequencies $\sigma(m_{\text{I}})$ to $\sigma(m_{\text{II}})$ along the line marked I. If the disturbance spectrum extends past m_{II}, waves of the second mode are also excited, *etc.* Hence, large disturbances will tend to generate waves of the fundamental mode and of frequencies near s_3.

Once a wave packet is formed, it will spread in horizontal extent, because the shorter waves move slower than the longer waves. The most prominent will be the least dispersive components, other factors remaining equal. The least dispersive waves will be those nearest the origin in fig. 12, for which the group velocity is most nearly constant and equal to the phase velocity.

Finally, higher modes will have proportionally lower amplitudes near the ground (where they were recorded). For very high modes, $\gamma_1 h \gg 1$, and the pressure disturbance hardly reaches the ground at all. In the case of a thin inversion layer, all modes higher than the fundamental die off rapidly above and beneath, and in the extreme two-layer case they vanish altogether at both sides of the infinitely thin inversion layer. This accounts for the absence of all higher modes in the two-layer model. Under the observed conditions (fig. 13), the second mode is only one-third lower at the ground than the fundamental mode, other factors remaining equal. This alone cannot account for the apparent absence of higher modes in the records.

Comparison between theoretical and observed wavelengths.—For the observed values of $\bar{U}$, the "Doppler shift" is small; hence, σ and $\bar{\nu}$ are nearly equal. It will be noted that $s_1 < \bar{\nu}$, $s_2 > \bar{\nu}$ and $s_3 < \bar{\nu}$. According to (8), n_1 and n_3 are then imaginary, n_2 is real, and (14) and (16) contain only real quantities. The equations have been solved for the horizontal wavelength $2\pi/m$, *with use of the observed values of* σ and ambient winds (lines 4, 8 and 10, table 2). Only the two gravest modes of an infinite number of roots to (16) have been evaluated.

The resulting wavelengths (lines 21 to 23, table 2) are of the same order of magnitude as those in line 20, which were derived from the impedance relation (1) and may be regarded as observed values. If $n_2 \Delta h \ll 1$, the two- and three-layer models should both yield values according to (16a). The two models do, in fact, yield similar values because $n_2 \Delta h < 1$ (but not $\ll 1$). The values are of the same order as those obtained by using the shallow "water" approximation (16b). The agreement is better for the fundamental mode L_{I} than for L_{II}, indicating a disturbance whose dimensions exceed L_{I} ($\approx$ 10 km).

Comparison between theoretical and observed wave periods.—In the theoretical discussion, it has been shown that waves of the fundamental modes and of low frequency are the ones most likely to be excited by a large initial disturbance (if there was one), that the least dispersive (longest) trapped waves are the ones most likely to persist and to be prominent near the ground (where the recordings were made). Hence, we should expect[7] frequencies between s_3 and s_2 and closer to s_3. This is roughly what the observations show (lines 8, 16 and 17, table 2).

The evaluation of s_3 is a matter of some uncertainty. The transition from the inversion layer to the upper air layer is not in reality abrupt, as assumed, and the selection of the effective upper lapse rate must remain to some extent arbitrary (see fig. 5). Furthermore, the soundings were not taken at the time and place of the recorded oscillations. With these shortcomings in mind, the observed frequencies are not inconsistent with foregoing conclusions, even though the agreement is not always impressive.

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[7] This is the conclusion reached by Martyn (1950) in a study of a two-layer model consisting of an upper layer and a ground-based inversion layer. Martyn assumes linear (rather than exponential) gradients in potential temperature. This complicates the solutions greatly without affecting numerical values appreciably. He also replaces the condition, $\partial p/\partial t$ continuous across the layers, by the boundary condition of a free surface at the inversion, $\partial p/\partial t = 0$. For a shallow inversion layer, this leads to the relationship $C\pi(s_2^2 - \sigma^2)^{-\frac{1}{2}}(\Delta h)^{-1} = 1/j$ instead of $= 2/(2j - 1)$, where $j = 1, 2, \cdots$ refers to the fundamental and higher modes. Thus, we obtain phase velocities about twice those of Martyn and in closer agreement with our observations.

ECHOGRAMS OF THE MID-PACIFIC EXPEDITION

by

ROBERT S. DIETZ, HENRY W. MENARD,
and EDWIN L. HAMILTON

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Echograms of the Mid-Pacific Expedition

ROBERT S. DIETZ, HENRY W. MENARD, and EDWIN L. HAMILTON

Summary—About 12,000 nautical miles of echograms (graphically recorded sea floor profiles) were obtained along straight runs between San Diego and the Marshall Islands on the Scripps Institution of Oceanography - U.S. Navy Mid-Pacific Expedition in 1950. This was the first extensive recorded profile ever obtained of the Pacific Basin so that much new topographic information was revealed.

Comparison of the Pacific sea floor profile with others across the United States and the Atlantic reveals the large scale roughness of the Pacific floor, the great size of the seamounts, and the presence of broad low swells.

The Hawaiian Islands are developed on one of these broad swells. Along the northeast side of the Islands there is a deep at the base of Oahu and Hawaii and an arch lying outside. It is believed the deep and the arch are related to crustal yielding in response to the load of the Hawaiian Ridge.

A mountainous region with many guyots was discovered between Hawaii and the Marshall Islands which is termed the "Mid-Pacific Mountains." A Cretaceous reef coral-rudistid fauna was dredged from the mile-deep top of two of the guyots, indicating great drowning.

Exclusive of the Mid-Pacific Mountains, thirty seamounts were crossed, many of which are new discoveries. Fourteen of these are higher than 5,000 feet and six are higher than 10,000 feet. A large guyot with a summit depth of 800 fathoms was discovered north of Midway. Several seamounts appear to have a depressed zone around their bases. Nearly all seamounts probably are of volcanic origin.

Three ridged scraps were crossed, viz., one 150 miles north of Bikini, another 200 miles southeast of Hawaii, and a third, the Mendocino Escarpment, west of California along latitude 40°. These ridged scarps mark abrupt regional changes in sea floor level and probably are formed by faulting.

Three U-shaped depression (grabens ?) were discovered. Two of them, although separated by 1,000 miles, may be developed in the same fracture zone.

Much of the sea floor is rough in topographic detail. This is especially true of the region between the U.S. and Hawaii. Sediment appears to be accumulating largely in the topographic lows forming flat basins over about 37‰ of the track. It seems necessary to assume that there are currents along the deep sea floor competent to erode sediment after it has once been deposited and move it into the lows.

INTRODUCTION

IN July 1950 the Scripps Institution of Oceanography of the University of California and the U.S. Navy Electronics Laboratory embarked on a four month oceanographic expedition to the Mid-Pacific. The vessels participating in this cruise were the research vessel *Horizon* of the Scripps Institution and the USS *EPCE* (*R*) 857 of the Navy Electronics Laboratory. Approximately, the intinerary of the two ships was from San Diego, California to Honolulu, Hawaii along a V-shaped track reaching almost to the equator ; then westward to Kwajalein and Bikini atolls in the Marshall Islands. The ships returned to San Diego via separate courses. The *Horizon* proceeded via Wake Island, Midway Island, and along the parallel of 40°N whereas the *EPCE* (*R*) returned via Johnson Island and Oahu. Fig. 1 is a sketch of the tracks of the two ships which together travelled almost 30,000 miles. Fig. 2, 3 and 4 are profiles of the sea floor obtained along the track. Some typical echograms are shown in Plates 1 and 2.

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A study of the bathymetry along the tracks of the vessels was one of about 15 separate scientific programs of the cruise. This was accomplished by the almost continuous operation of the Navy model NMC-2 echo sounder (manufactured by the Submarine Signal Co.) on each vessel which graphically records 17 kc sound pulses reflected from the sea floor. The normal maximum recording range of this echo sounder is 2,000 fathoms but this range was extended by means of a slight modification to the equipment.

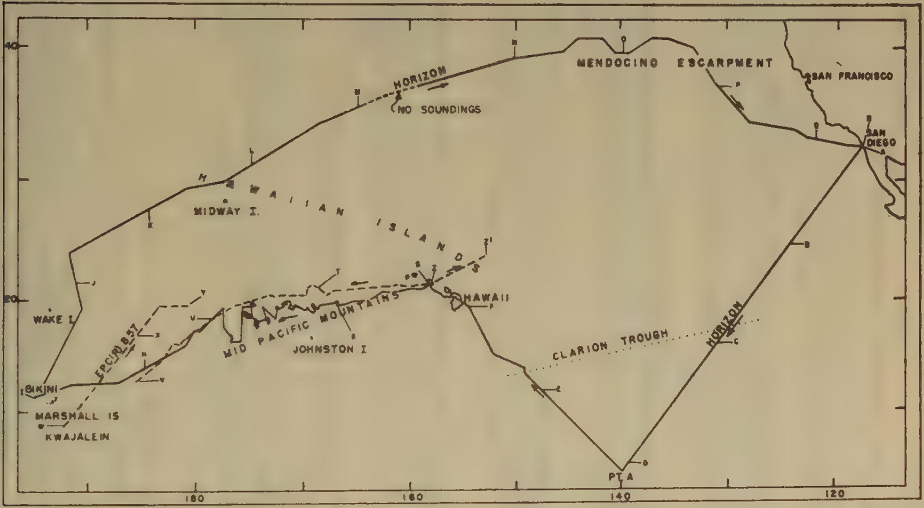

Fig. 1. Track chart showing the course followed by the research vessels *Horizon* and *EPCE* (*R*) 857 on the Mid-Pacific Expedition. The track of the *Horizon* is indicated by a solid line and the locations of sea floor profiles shown in Fig. 2 and 3 are shown by the letters *A* to *R*. The portions of the *EPCE* (*R*) 857 track for which bottom profiles are plotted on Fig. 4 are shown by the dashed line and the letters *T* to *Z*. The General location of the Mid-Pacific Mountains, the Mendocino Escarpment, and the Clarion Trough is also indicated.

Some of the bathymetric results of this Scripps-Navy 1950 Mid-Pacific Expedition have already been reported. MENARD and DIETZ (1952) have described the 1,200 mile-long and 3,000 to 10,000 feet high Mendocino Escarpment discovered along parallel 40°N west of Cape Mendocino, California ; DIETZ and MENARD (1952) have described and attempted to interpret the bathymetry in the vicinity of the Hawaiian Islands ; and HAMILTON (1951a, 1951b, 1953) has described the bathymetry and the fossil pelagic Foraminifera and macrofossils of the Mid-Pacific Mountains which lie completely submerged between the Hawaiian Islands and Wake Island. This paper is a discussion of the over-all bathymetric results with emphasis on those regions not covered in the preceeding papers.

PROFILES ACROSS PACIFIC SEA FLOOR AND NORTH AMERICA COMPARED

In Fig. 5, portions of the section shown in Figs. 2 and 3 are compressed to a vertical exaggeration of 100 so that they can be directly compared with profiles prepared by SHEPARD (1948, Fig. 94) across the United States and across the South Atlantic. This comparison emphasizes the great distance traversed on the Mid-Pacific Expedition and relates the scale of sea floor relief to well known physiographic features.

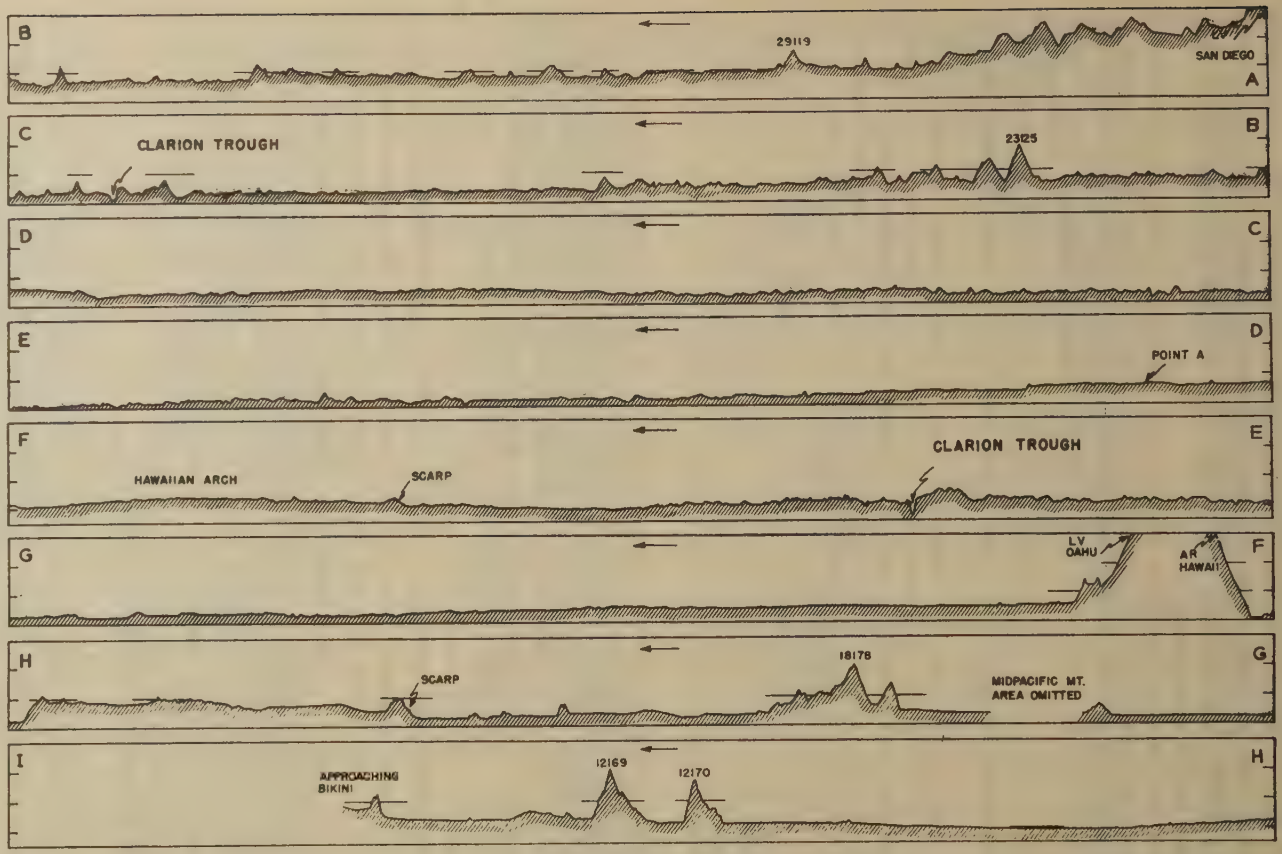

Fig. 2. Sea floor profile obtained by the *Horizon* on the Mid-Pacific Expedition on the outgoing passage from San Diego to the Marshall Islands. See Fig. 1 for the location of the profiles. Dashed portions of the bottom show where the echogram was difficult to read with certainty. Depth is shown by the indices at the right and left margins which mark 1,000 fathom intervals. The arrows indicate the direction of ship travel. Many of the seamounts are indentified by a number, the first two digits giving the location in latitude and the last three giving the longitude to the nearest degree. The profile is shown with a vertical exaggeration of 12 times.

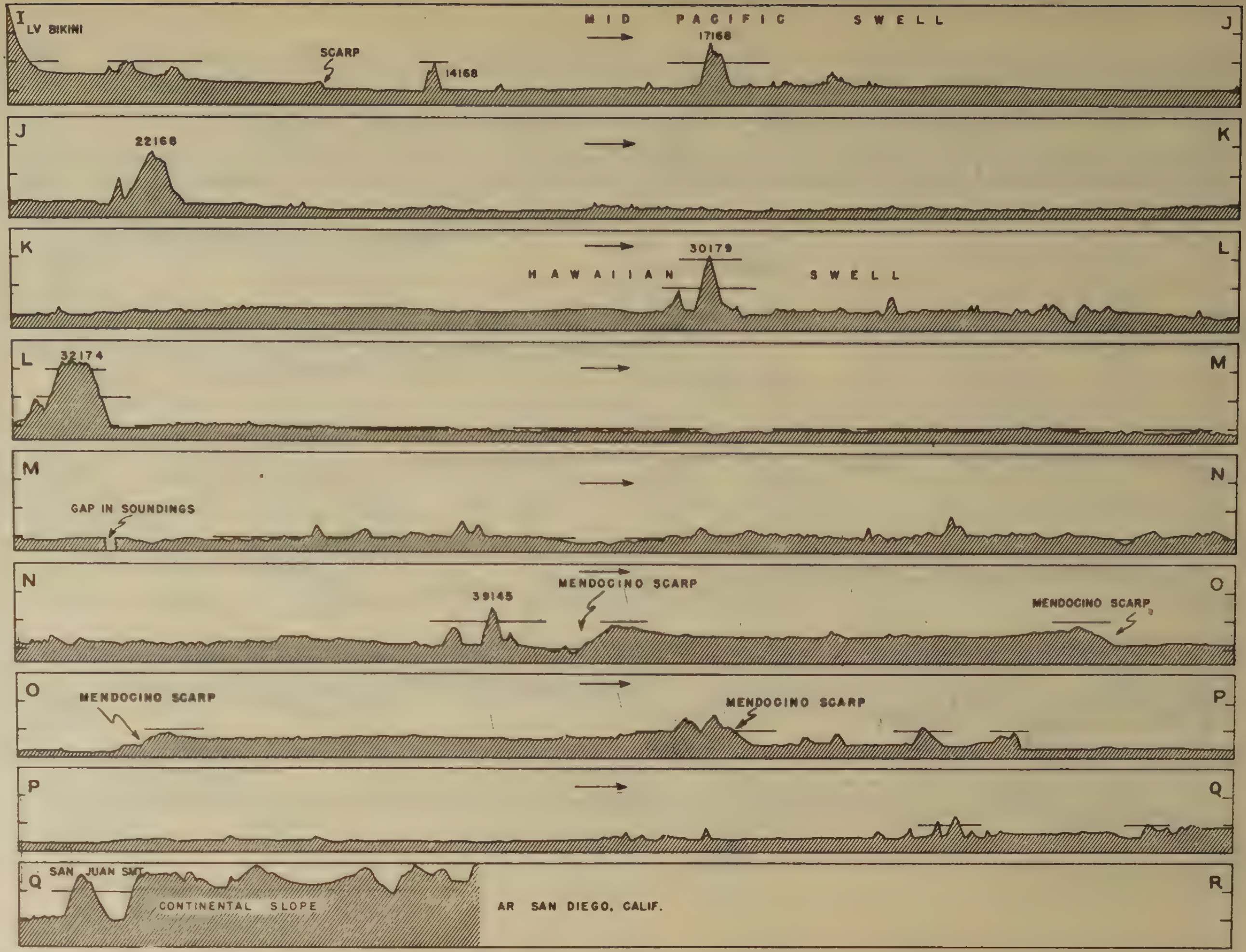

Fig. 3. Sea floor profiles obtained by the *Horizon* on the return passage from Bikini to San Diego showing the Mid-Pacific Swell, the Hawaiian Swell, and four crossings of the Mendocino Escarpment. The track for this profile is shown in Fig. 1. See caption to Fig. 2 for detailed explanation of the showing of the profile.

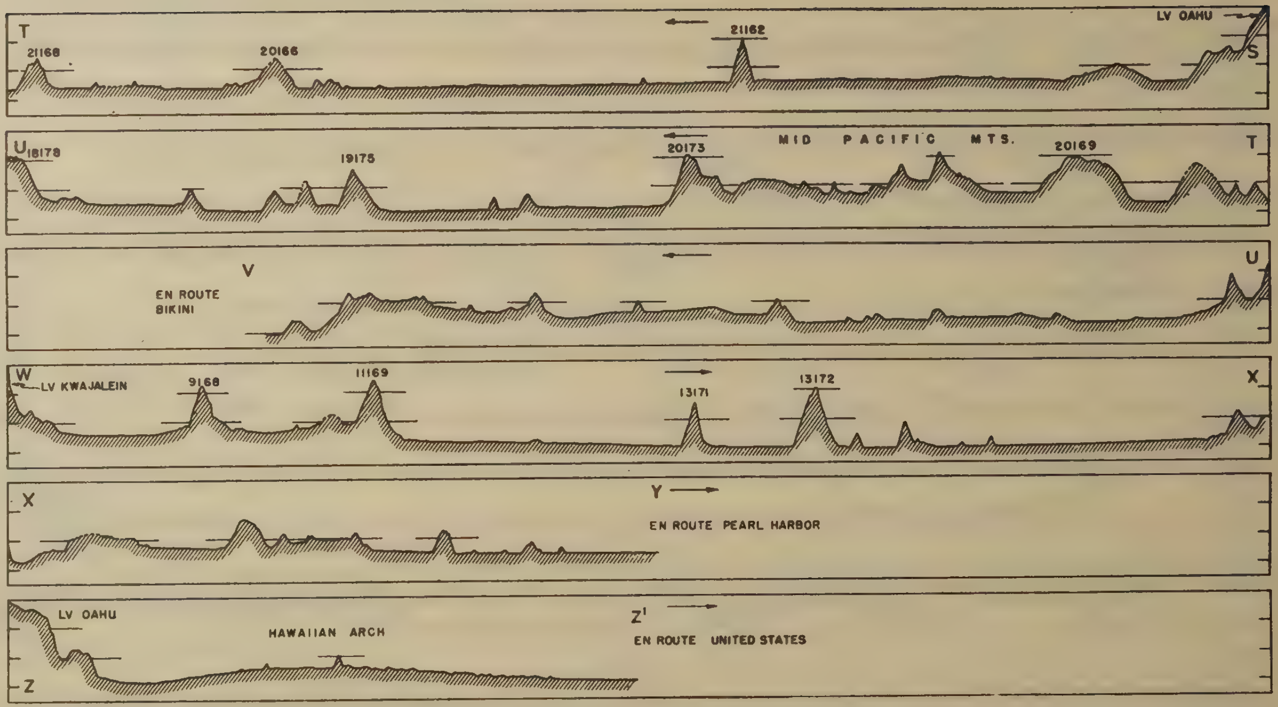

Fig. 4. Sea floor profiles obtained by the *EPCE* (*R*) 857 on the Mid-Pacific Expedition, 1950, for the region from Oahu to Bikini, from Kwajalein toward Oahu, and from Oahu across the Hawaiian Swell toward the U.S. See the caption to Fig. 2 for details of the method of drawing and see Fig. 1 for the location of the track.

Perhaps the most striking aspect is the size and the great height of Hawaii. Mauna Kea (elev. 13,784 ft.) lies only 39 nautical miles southwest of a sounding of 3,040 fms giving a relief of 32,024 ft. over this short distance. According to H.O. chart 5653, the deepest sounding in the Hawaiian Deep is 3,280 fms so that the total relief from this point is 33,505 making Hawaii by far the highest mountain in the world.

The profile also emphasizes the Mid-Pacific Swell and the Hawaiian Swell from which high seamounts rise comparable to and, in some instances, even higher than the Sierra Nevada. None of the swells, however, have the vertical relief of the elevated region of the western United States or of the Mid-Atlantic Ridge. It can also be seen that no stretch of the sea floor is as smooth, on this scale, as the region extending from the Great Plains to the Appalachian Mountains.

The large scale of the Mendocino Escarpment is also apparent by comparing it to the Appalachian Mountains, for example, which on this scale are a minor feature. The Mendocino Escarpment varies from ½ to 2 miles high and extends at least for a distance equivalent to that from New York to Denver.

HAWAIIAN REGION

During the Mid-Pacific Expedition, profiles were obtained of the sea floor structure around the Hawaiian Islands in the vicinity of Oahu, Hawaii, and Midway (Fig. 1). A study of these Hawaiian structures has already been published (DIETZ and MENARD, 1953) so that only a brief summary need be given here.

The fundamental structure of the Hawaiian region appears to be a long, low and broad rise in the sea floor, the Hawaiian Swell or Rise which is about 3,000 feet high, 600 miles across, and 2,000 miles long, extending from near Hawaii Island to far beyond Midway Island. A long narrow and high ridge, the Hawaiian Ridge, is superimposed on the swell, and the Hawaiian Islands are, of course, merely the above water portion of this ridge. A depressed zone, deep, or " moat " is present along the north-east side of Oahu and along the northeast and hooking around to the south side of Hawaii.

Seaward of the depressed zone, the sea floor is arched up over a distance of more than 200 miles. The two crossings across the arch made 10 miles apart southeast of Hawaii, show an abrupt ridged escarpment marking the outer limit of the arch (Plate 1, Profile C) which almost certainly was formed by a fault. However, east of Oahu, the outer limb of the arch gradually merges with the deep sea floor and no fault is present (Fig. 4, Profile Z-Z′). Along the inner limb of the arch the sea floor is smooth but along the outer limb the bottom is rough. More recent information shows that this contact between smooth and rough bottom marks the beginning of the Baja California Seamount Province (MENARD, in press), a major geomorphic province in the north-east Pacific. This province, which extends from the top of the Hawaiian Arch to the base of the continental slope off southern California and Baja California, is characterized mainly by bottom with roughness of moderate amplitude and with many large seamounts.

It is considered that the Hawaiian structure is related to vertical forces which have arched up the crust and produced tension fractures out of which lava has poured. Arching of the sea floor above the zone of divergence in two thermal convection cells in the earth's mantle might account for the Hawaiian Swell. Deep

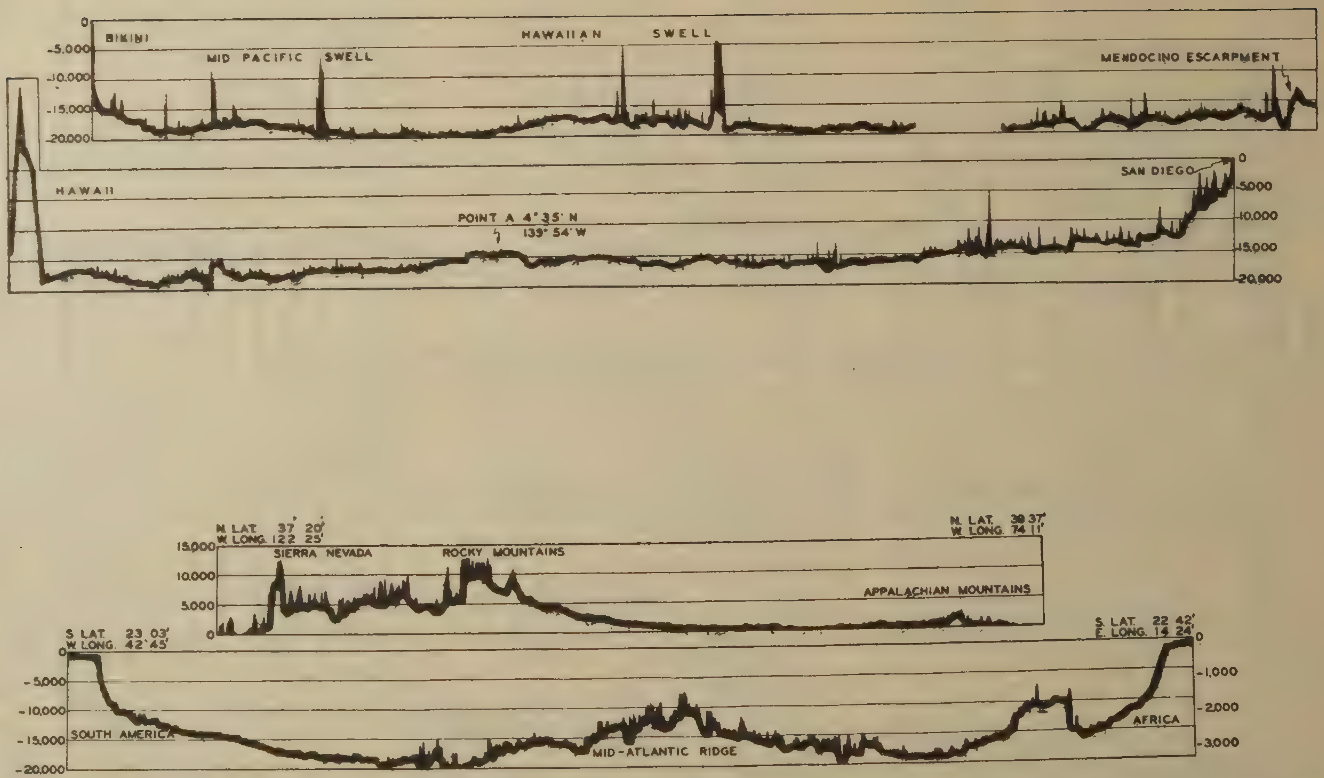

Fig. 5. Compressed profiles of portions of the bottom of the Pacific from the Mid-Pacific Expedition compared to profiles (from SHEPARD, 1948, p. 282, fig. 94) across the United States from Geological Survey topographic sheets and across the South Atlantic from *Meteor* soundings. Vertical exaggeration is 100 times. Elevations and depths are marked in feet.

terraces at depths as much as 700 fathoms around the Hawaiian Islands appear to be drowned shelves and suggest that the Hawaiian Islands have isostatically subsided, owing to overloading of the crust. Further evidence is provided by the moat and the Hawaiian Arch as they also may be caused by a regional yielding of a semi-rigid crust. The presumed fault present at the outer edge of the arch off Hawaii may have been formed by failure of the crust to this stress imposed by the Hawaiian Ridge. Here, as in the region of the arch, the stress is directed upward.

MID-PACIFIC MOUNTAINS

A special exploration was made of a mountainous area between the Hawaiian Islands and Wake Island because existing sounding showed the presence of a number of flat-topped seamounts of the type which have been termed " tablemounts " or " guyots " (HESS, 1946). About 2,000 nautical miles of soundings were recorded in this region between 167° and 169°W Long. and 16° and 20°N Lat. by the *Horizon* and by the USS *EPCE* (*R*) 857. The results of this work have been reported in detail by HAMILTON (1951a, 1951b, 1953, in press) so that they will be only briefly summarized here. Inasmuch as there was complicated maneuvering through this region, the bottom profiles are not shown on Fig. 2 but a small section is shown in Fig. 4.

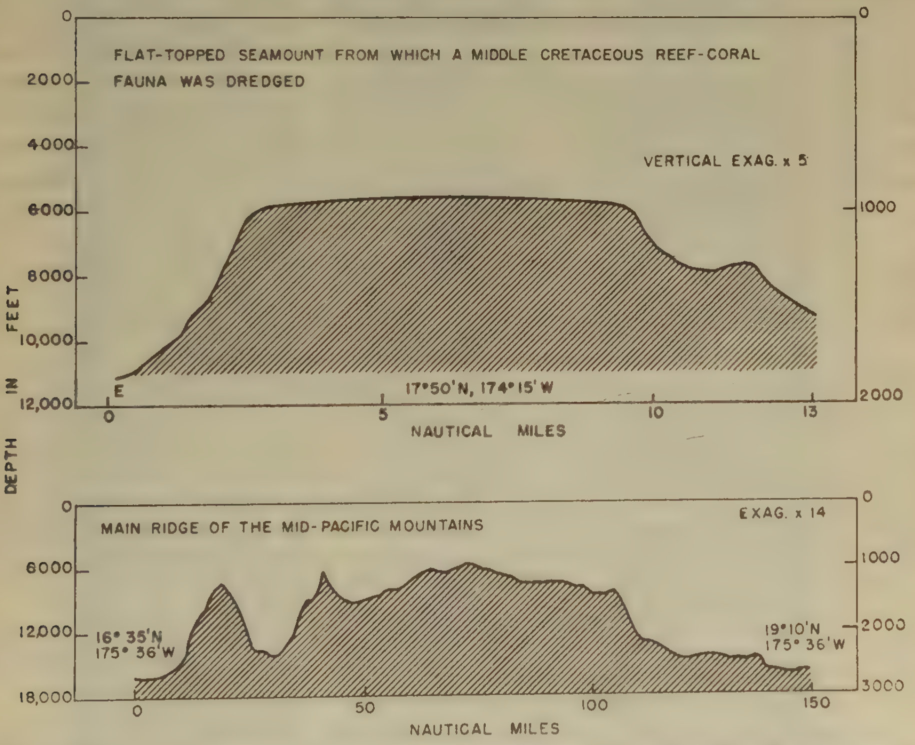

Fig. 6. Top : A profile of one of the guyots (Hess Guyot) in the Mid-Pacific Mountains from which a Cretaceous reef coral rudistid fauna was dredged. Note that flat top and the abrupt break-in-slope at the edge of the summit. Bottom : A profile across the main ridge of the Mid-Pacific Mountains.

The soundings from the expedition plus earlier soundings revealed the presence of a rugged and topographically high region extending from Necker Island in the Hawaiian Islands to the vicinity of 170°E Long., a distance of about 1,450 nautical miles (Profiles A and B, Plate 1). The name " Mid-Pacific Mountains " was adopted for this east-west structure. Near Necker Island the structure is only 25 miles wide but it reaches a maximum width of 600 miles between 180° and 175°E Long. Structurally the Mid-Pacific Mountains appear to be a low, broad east-west swell in the sea floor upon which are superposed numerous large volcanic seamounts many of which are flat-topped. Fig. 6 (top) shows a profile across one of these guyots. Linear trends in some places indicate that faulting may have been of some importance in the formation of this mountain range. A study of U.S. Navy Hydrographic Office soundings shows that this zone of shallow topography and numerous seamounts commences again at Wake Island and continues at least to Marcus Island. This may be an extension of the Mid-Pacific Mountains structure because the passage of the *Horizon* through the saddle region when returning to San Diego (Fig. 3 Profile I-J and Fig. 5, top) revealed a broad, low swell.

Five flat-topped seamounts of the main range were cored and dredged. Four of these were indicated by existing soundings ; the fifth was a new discovery. These guyots have flat tops between 700 and 900 fathoms and the side slopes are concave upward with a maximum slope of about 20 degrees near the top. They are symmetrical in profiles and oval in plans with the exception of one which is a flat-topped ridge. All of the five seamounts have perceptible breaks-in-slope between the upper

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PLATE 1. (*right*) MID-PACIFIC EXPEDITION ECHOGRAMS SHOWING TROUGHS, SCARPS, AND A MID-PACIFIC MOUNTAIN PROFILE.

All soundings are on deep scale so that the depth in fathoms indicated on the printed scale must be multiplied by five. In addition, all profiles, except the tops of seamounts which jut far above the usual level of the bottom, are on the 2,000 fms-plus scale so that 2,000 fms must also be added. Thus a depth reading of 190 ordinarily equals 190 × 5 plus 2,000 or 2,950 fms. Those portions of the echogram which are shoaler than 2,000 fms are indicated with ruled lines. The standard underway speed of the ships was 12 knots. The printed ordinates on the echogram represents twenty minute intervals so that three of these equals one hour or a distance of 12 nautical miles. The vertical exaggeration of the profiles is, therefore, about 25 times. The recording stylus of the NMC-2 echo sounder rotates in a circle so that the profile is not rectilinear but rather arcuate. The depths of the echograms are uncorrected and are based on the standard sounding speed of 4,800 ft./sec. Thus, the sea floor is in all cases deeper than indicated by about 2 per cent up to 1,800 fms and by about 3 per cent at 3,000 fms.

(A) A profile across a section of the Mid-Pacific Mountains showing the mountainous topography of the region. The eastermost seamount (right hand side of the echogram) has a minimum depth of 970 fms and has a beveled top so that it is a guyot. In the center of the profile there is a perched basin, higher than those flanking the range to the east and west.

(B) A continuation of profile " A " to the west (left).

(C) Ridged scarp marking a regional change of 160 fms in the level of the sea floor and marking the beginning of the Hawaiian Arch 200 miles southeast of Hawaii Island. Northwest is to the right. Regional location shown on Profile E-F of Fig. 2.

(D) A ridged scarp, with an essentially vertical face of 250 fms relief, which marks a regional change in sea floor level separating the rise on which the Marshall Islands are developed from a deeper portion of the Pacific floor to the northeast. The bottom here is smooth. This profile is also drawn on Profile I-J of Fig. 3. Seamount 14,168 is shown near the east (right) end of the section.

(E) Echogram of the sea floor showing the eastern crossing of " Clarion Trough " which reaches a depth of 2,900 fms. This section is also shown in Profile B-C of Fig. 2.

(F) West crossing of " Clarion Trough " in the Clarion fracture zone. The maximum depth is 3,320 fathoms uncorrected (i.e. about 3,430 fms true depth) which is the greatest depth encountered on the Mid-Pacific Expedition. This profile is also shown on Profile E-F of Fig. 2.

(G) The irregular crest of the Hawaiian Swell is displayed in this profile. Note the large trough which descends to 3,150 fms. This trough is about 5 miles across and is 300 fms deeper than the regional level of the floor. This profile is also shown on Profile K-L of Fig. 3.

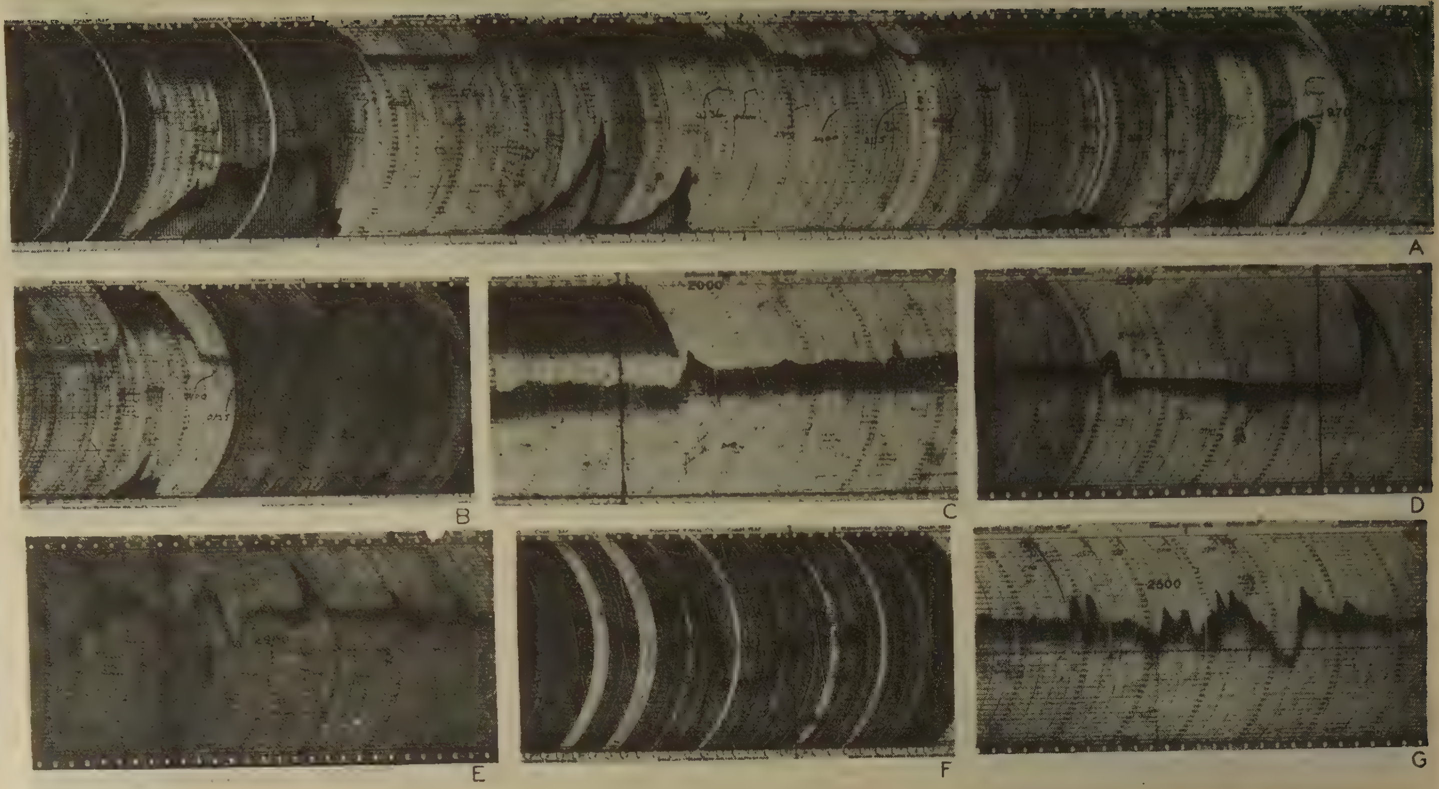

PLATE 1.

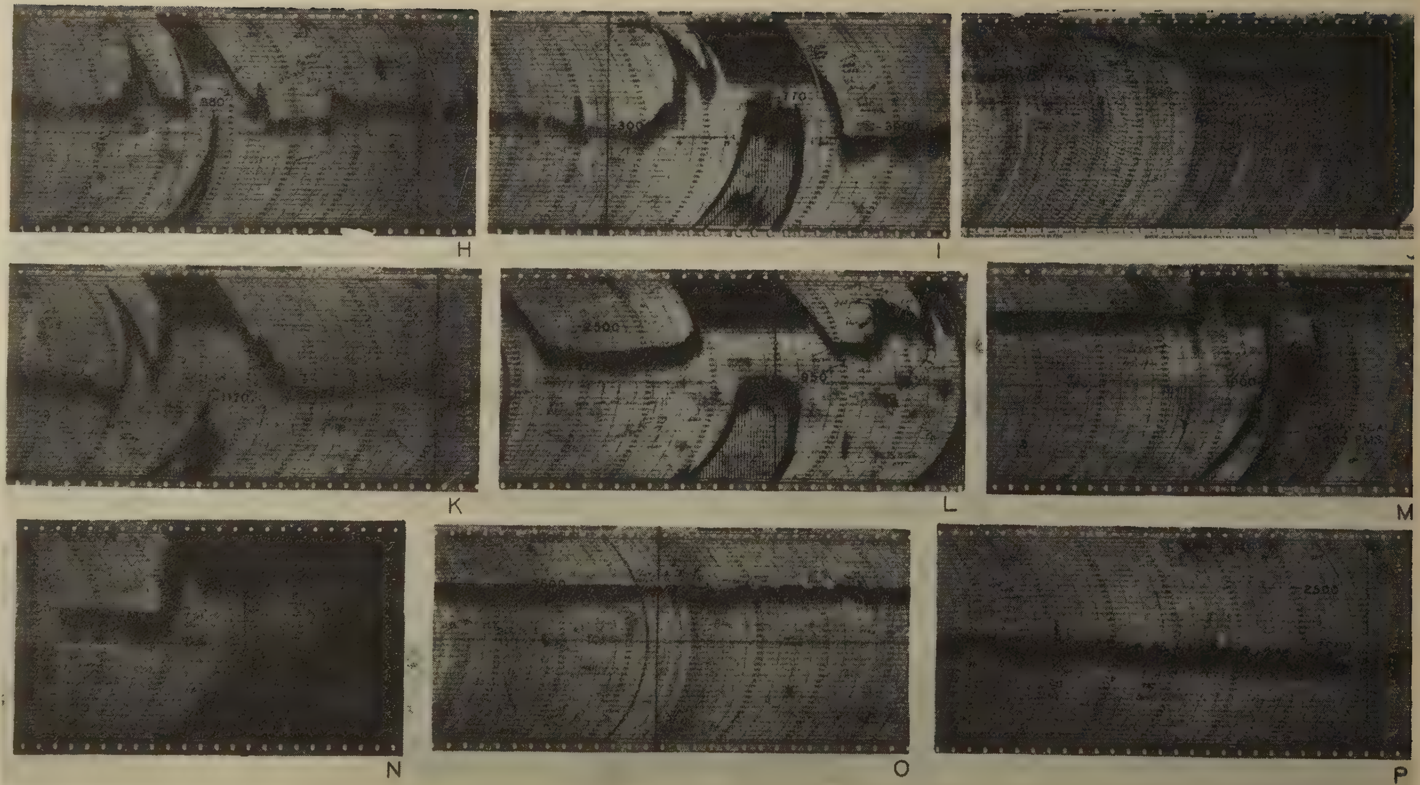
880
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PLATE 2.

side slope and the flat tops. Within the range of summit heights, there do not seem to be any preferred levels. The data are too few to allow other than a random distribution of heights to be assumed.

In accordance with the plan of the expedition, the dredging was done largely at the margins of the flat tops of the guyots in an attempt to recover fossil remains of shallow water organisms. It was believed that the guyots might possibly be deeply drowned coral reefs. This belief was confirmed by the recovery from two seamounts of a well-integrated fossil fauna of reef coral, rudistids, stromatoporoids, gastropods, pelecypods, and an echnoid. At both localities, the age of the assemblage is Cretaceous (Aptian to Cenomanian) with affinities for the faunas of the Tethyan Province. Fig. 6 (top) shows the seamount from which the major portion of the fossil reef coral assemblage was dredged. In each case, volcanic rock was recovered in the same haul or in a nearby haul so that these guyots appear not to be drowned atolls but, instead, drowned basaltic platforms on which some reefs grew.

The tops of the guyots are covered with globigerina ooze, basaltic detritus, and bedrock. Rounded sand grains, pebble, cobbles, boulders of olivine basalt, and sand-

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PLATE 2. (*left*) MID-PACIFIC EXPEDITION ECHOGRAMS SHOWING SEAMOUNTS AND OTHER FEATURES ENCOUNTERED IN THE NORTH PACIFIC OCEAN.

For method of reading the echogram refer to explanation for Plate 1.

(H) A profile across the Hawaiian Swell showing the irregular form of the bottom and showing Seamount 30.179 rising to 890 fms. The pointed form of the feature indicates that it has been "sideswipe," i.e. the profile goes over the flank of the seamount and not over the summit. This profile is also shown on Profile K-L of Fig. 3.

(I) Seamount 32,174, which rises from 3,080 fms to 770 fms, has a total relief of 13,860 feet. This seamount appears to have a truncated summit suggesting that it is a guyot even though the summit topography is rough. The sea floor on both sides of the seamount is depressed below the regional level suggesting that an annular depression or "moat" may be present. This profile is also shown on Profile L-M of Fig. 3.

(J) A unique asymmetric feature encountered on the Mid-Pacific Expedition immediately west of Oahu. This asymmetrical block rises 600 fms from a regional depth of 2,500 fms. The bottom is level to the east at the base of Oahu but slopes to the west. This slope appears to be a flank of a poorly developed arch on the southwest side of the Hawaiian Islands.

(K) Seamount 22168 encountered on the return passage from Bikini to the U.S. It lies between the Mid-Pacific Swell and the Hawaiian Swell. If the summit was crossed, this seamount has an irregular top and hence is a seapeak rather than a guyot or tablemount. This profile is also shown on Profile J-K of Fig. 3.

(L) A large-flat-topped seamount or guyot in the Mid-Pacific Mountains is shown in this profile. It rises from 2,700 fms to 950 fms which is typical of the summit depth of the guyots of this region. Note the abrupt break-in-slope at 1,050 fms on the west (left) side and the bevelled slope rising to the summit. If a profile of the seamount were drawn without the 25 times vertical exaggeration, the flatness of the top would be more apparent.

(M) Echogram showing the flank of Bikini Atoll. The sea floor is about 2,400 fms deep and it descends slightly toward the base of the Atoll. The side rises abruptly to 1,000 fms where the slope becomes even steeper possibly marking the contact between the volcanic seamount and coral talus. At 400 fms the echo sounder was switched to shoal scale (0-400 fms for the width of the paper) so that a blown up view of the top 400 fathoms is presented. In this portion of the echogram, a profile through a pass in the reef and into the lagoon which has a depth of 27 fms is shown. The level stretch near the top of the atoll is caused by the ship running parallel to the contours for several minutes. The long echo extension shows that the bottom is actually steep.

(N) This profile shows smooth sea floor abutting against the base of a seamount in the Mid-Pacific. It is especially noteworthy that the sea floor is bent down as the seamount is approached, suggesting that the bottom has yielded to the load of the seamount.

(O) A profile between Oahu and the Mid-Pacific Mountains showing the contact between rough and smooth bottom at 2,500 fms. Between the large seamounts, such smooth bottom was characteristic of the track between Hawaii and the Marshalls. Rough bottom characterized the track east of Hawaii. The stretch of sea floor is shown in the middle of Profile G-H of Fig. 2.

(P) A 120-mile stretch of the sea floor on the eastern flank of the Hawaiian Swell east of Midway which deepens to east (left). Minor roughness, with an amplitude of about 50 fms, characterizes this flank of the Hawaiian Swell. This profile is redrawn as the middle portion of Profile L-M of Fig. 3.

stone with minerals derived from basalt were recovered. The lithology is similar to that of the Hawaiian Islands. Some of the cobbles were too well rounded to have formed in their present enviromennt. They appear to have been rounded under conditions of vigorous current action such as is found in the surf zone.

A study of the globigerina ooze from the Mid-Pacific Mountains (HAMILTON, 1953) has revealed the presence of an extensive pelagic fossil fauna. Foraminifera of Cretaceous (Campanian-Maestrichtian), Paleocene, Eocene, Oligocene, Miocene, and Recent age have been identified. The fauna is in an excellent state of preservation without evidence of corrasion or solution.

The writers interpret the geologic history of the Mid-Pacific Mountains as follow: A broad swell formed in the sea floor at some time prior to the Middle Cretaceous. This arching of the sea floor may have formed above the divergence of two thermal convection cells in the earth's mantle. Tensional fissures developed in the arch out of which lava poured forming numerous large volcanos. Some of the larger of these volcanos pierced the surface of the ocean and thus became islands. It is believed that extensive horizontal buckling of the crust such as has formed the folded alpine mountains on the continents has not taken place here. This sequence is similar to that proposed by DIETZ and MENARD (1953) for the Hawaiian Islands. These islands were then truncated by subaerial erosion and wave action and Cretaceous coral reefs grew on the shelves around these islands. Subsequently the islands began to sink. Some unfavourable ecological conditions or rapid initial sinking prevented the coral reefs from keeping pace with the subsidence of the banks so that the reefs were killed. Subsequently subsidence continued to the present depth of the guyots of about 1 mile. The writers consider the drowning to be largely the result of regional yielding of the earth's crust to the load of the Mid-Pacific Mountains and local yielding to the load of the particular guyot rather than an absolute rise of sea or to some other cause.

The macro-fossils from the Mid-Pacific Mountains are the oldest yet recovered from the Pacific Basin. Assuming that guyot summits are structurally undeformed so that the reefs are in their original position except for submergence, they give evidence that the Pacific Basin is at least as old as Aptian-Cenomanian. They also show that the Pacific Basin was a deep sea basin in the Cretaceous, because, although they are one mile below present sea level, they are two miles higher than the general level of the sea floor. The supposition of HESS (1946) that the summits of the guyots subsided below sea level in pre-coral reef time (Pre-Cambrian) is disproved.

SEAMOUNTS

Exclusive of the Mid-Pacific Mountains where numerous seamounts were found, thirty seamounts were crossed, many of which are new discoveries. (Seamounts are defined as isolated rises with more than 500 fathoms relief, i.e. 3,000 ft. or about 1,000 m and isolated rises smaller than this are termed seahills or seaknolls). Fourteen of the seamounts have crossings which are higher than 5,000 ft. and 6 are higher than 10,000 ft. Surveys were not made so that the minimum depths are not known.

Several guyots were discovered in the Mid-Pacific Mountains (HAMILTON, 1951b; in press) and Sylvania Guyot near Bikini Atoll was surveyed and sampled in considerable detail. The bathymetry and sediments from Sylvania Guyot are discussed by EMERY, TRACEY and LADD (in press) and the volcanic rocks which were dredged are discussed by MACDONALD (in press). Otherwise, only one guyot, Seamount 32174, was found. (Profile L-M of Fig. 3 and Plate 2, I). However, some of the other seamount profiles are almost certainly flank crossings which did not pass over the summit. Future detailed surveys of these may show that some are guyots.

Irregular depressed profiles were found at the base of three large seamounts (30179, 32174, and 21162). At the base of three others (21162, Bikini Atoll, and a seamount in the Mid-Pacific Mountains) the sea floor is smoothly downbowed. The last two named are figured in Plate 2, M and N. Judging from the Hawaiian Islands, which were discussed earlier, it appears likely that these profiles are across depressed zones or " moats " which extend around these seamounts. It seems probable that such saucer shaped depressions are formed by semi-rigid yielding of the crust to the load of the seamounts. However, the possibility cannot be eliminated that they are caused by foundering following the extraction of magma during the formation of a volcanic seamount.

Volcanic rocks were dredged from five seamounts in the Mid-Pacific Mountains and from Sylvania Guyot, bearing out the probable volcanic nature of most seamounts which is apparent from their conical shape. One seamount (Plate 2, J), however, has an asymmetrical form, suggesting that it is a fault block.

RIDGED SCARPS

Along the track of the Mid-Pacific cruise three large escarpments were crossed. These are not simply a step-like displacement of the sea floor but rather are a step-like displacement upon which is superposed an asymmetrical ridge. Thus, they can be termed " ridged scarps." Profiles of two of these are shown in Plate 1 (Profiles C and D). The first was encountered at lat. 16° 20′N, long. 153° 00′W, about 220 miles southeast of Hawaii. The second was found at lat. 14°00′N and long. 166°40′E, 150 miles northeast of Bikini. The third is the Mendocino Escarpment, located along latitude 40°N and extending west of Cape Mendocino. This enormous escarpment is from 3,500 to 10,000 ft. high and more than 1,200 miles long. It is the subject of a separate paper by MENARD and DIETZ (1952) to which the reader is referred for a detailed description.

In all these scarps there is a regional difference in level of the earth's crust between the two sides. The Hawaiian and the Marshall Island scarps separate a regional change in level of about 1,000 ft. whereas the Mendocino Escarpment separates a regional change of about 3,000 ft.

The scarp face may be quite steep. Assuming that the sound cone had a half-angle of 30°, the Marshall scarp, for example, is essentially vertical for over 1,000 ft. The Mendocino Escarpment averages 10° and has maximum slopes of about 30°. The presumably volcanic slopes of seamounts are generally about 10° but sometimes are as much as 22°. Slopes greater than this strongly suggest faulting.

The ridged scarps may have considerable linear extent. The Mendocino Escarpment is known to be more than 1,200 miles long. The Hawaiian scarp was crossed on two tracks ten miles apart. Only one crossing was obtained of the Marshall scarp so its linear development is not known.

The steepness, the linear extent, and the regional difference in level of the sea floor all suggest that these scarps are fault scarps marking major fractures in the earth's crust. A possible mode of origin of the Hawaiian scarp already has been discussed. The crustal blocks bounded by the Mendocino Escarpment are of large size so that they must be presumed to be in isostatic equilibrium. Thus the higher level of the north block as compared to the south block may reflect a change in rock density. The scarp, with its complex structure, may have formed along the transition zone between two regions of different crustal composition.

By using recent soundings, MENARD (in press) has found that the Mendocino Escarpment is one of four sub-parallel fracture zones that extend in a roughly E-W direction, following the arcs of a great circle, in the northeast Pacific Ocean. The " Clarion " Trough, discovered on the Mid-Pacific Expedition, forms part of one of these zones.

U-SHAPED DEPRESSIONS

Three large U-shaped depressions were found along the tracks of the vessels on the Expedition. The echograms of these are reproduced in Plate 1, E, F, and G. One U-shaped depression was encountered along the crest of the Hawaiian Swell north of Midway. Two others were discovered east of Hawaii. Although these are 1,000 miles apart, MENARD (in press) has shown that they probably occur in different parts of a long fracture zone in the northeast Pacific which he has termed the " Clarion Fracture Zone." It is believed that many troughs are discontinuously present along this zone.

It is supposed that these troughs are large grabens. They are topographically quite different from the trenches or foredeeps associated with island arcs.

SMALLER TOPOGRAPHIC FORMS

In this paper, smaller topographic forms include all the features which have less relief than seamounts and which are not identifiable as escarpments, swells, etc. The echo sounders used scan an area of the bottom with a diameter of about one half times the depth ; thus these instruments are not able to resolve features on the deep-sea floor which would be termed minor relief on land. Small valleys and depressions would have been completely missed.

The sea floor along the track between California and Hawaii is notable for its minor irregularities which yield a jagged trace on the fathogram (Profiles A-F of Fig. 2). Off Baja California, no areas of flat bottom were crossed for hundreds of miles, although the side slopes of many topographic features are no greater than 1½ degrees. Representative features are two to four miles wide and from 300 to 1,800 ft. high. Between 17°N latitude and Point A, the smaller topographic features are more subdued, more rounded, and less symmetrical in profile than those off Baja California. Representative features are three to nine miles wide and 300 to 1,200 ft. high.

Another area displaying minor irregularities rather than smooth bottom or major topography was crossed between the Hawaiian Swell and the Mendocino Escarpment (Profiles L-M and M-N of Fig. 3). The individual features are roughly two to four miles wide and 300 to 1,200 ft. high.

The origin or origins of the smaller topographic forms cannot be determined from the MidPac fathograms. Numerous minor jogs in course were made over these rough areas, as elsewhere, in order to take routine measurements of surface currents. Consequently, the relief in three dimensions can be established for very limited areas a few miles on a side. These " surveys " suggest that most of the features are hill-like, i.e. equidimensional rather than linear, although the side slopes are very gentle.

The great depth of the " hills " appears to obviate any possibility of a subaerial erosional origin. Nor does differential deposition of sediment or submarine erosion seem a plausible explanation for topographic highs. By elimination, the " hills " must be produced by vulcanism or folding and faulting. Some of the higher features with steeper slopes undoubtedly are the flanks of major seamounts. The more asymmetrical features may be fault blocks particularly between Hawaii and the Mendocino Escarpment where most of the track appears to lie near a major fracture zone which extends west from the Mendocino Escarpment. The " hills " off Baja California may be very low volcanic cones or fissure lava flows.

BASINS OF SEDIMENTARY ACCUMULATION

By visual inspection of the bottom profiles, an estimate was made of the percentage of smooth or nearly smooth bottom as compared to the percentage of rough bottom. This examination showed that 37% of the sea floor crossed by the Expedition is smooth and 63% is rough. Inasmuch as the smooth regions occupy the topographic lows, it can be assumed that they are areas of sedimentary accumulation. In recent years coring from vessels equipped with echo sounders has tended to establish the principle that smooth bottom indicates unconsolidated sediment whereas rough bottom is generally rocky. Although sediment is encountered in the rough areas, it seems probable that it forms only patches or a thin cover supported by a " backbone " of bed rock. Thus, almost two thirds of the sea floor traversed on the Mid-Pacific Expedition may be rock only patchily covered with sediment.

Rough bottom especially characterized the first leg of the Expedition between the U.S. and Hawaii, although several small smooth basins were found near the U.S. These basins may be related to the shedding of sediment by the North American continental block. The filling of these basins is most evident near the continental slope and decreases to the west, suggesting such a directional source of the sediment. Another area of smooth bottom was found in the vicinity of Point A. This may be related to the high production and consequent rapid deposition of pelagic organisms beneath the Equatorial Counter Current. Between the Hawaiian Islands and Bikini extensive flat basins were found flanking the Mid-Pacific Mountains and between the large seamounts of this range. The discovery of this apparently extensive and deep fill of sediment was surprising inasmuch as the region is far removed from the continental blocks and the organic production in these water is small. It seems necessary to assume that this is a region where sediment has accumulated during an extremely long period of time without any rejuventation of the bottom topography by tectonism or extrusion of lava flows. The Cretaceous age (HAMILTON, 1952 ; 1953) of the Mid-Pacific Mountains tends to support this point of view and by contrast suggest a Cenozoic age for the rough unsmothered topography of the first leg.

On the return passage from Bikini to the U.S., rough bottom was found to characterize the Hawaiian Swell but some areas of smooth bottom were found between this swell and the Mendocino Escarpment. South of the Mendocino Escarpment, an extensive smooth basin was traversed about 400 miles west of San Francisco. From previous work (MENARD and DIETZ, 1951) it is known that the region of the Gulf of Alaska north of this scarp also has an extensive smooth sea floor sloping to the southwest.

It is clear that there is little basis for the common assumption that the sea floor is a smooth featureless sedimentary plain upon which sediments everywhere accumulate at a uniform rate. Instead it appears that sea floor topography is determined largely by tectonic movements and volcanic extrusions. The principal role of sedimentation is to fill in the topographic lows. The localization of sedimentation in the basins and the apparent absence of a draped cover of sediments over all the sea floor topography makes it evident that horizontal transportation of sediments takes place along the bottom. Such movement along the bottom and the localization of deposition in basins must be taken into consideration by those who attempt to determine the rate of deposition in the deep sea as a whole by radioactive or other measurements on cores obtained from the sites of deposition.

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UTILIZATION OF DISSOLVED CALCIUM BY A PELECYPOD[1]

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University of California, Los Angeles

ONE FIGURE

Despite the intense interest exhibited in recent years concerning the nature of uptake and the primary source of calcium for shell formation in marine molluscs, the subject is still controversial. Orton ('25) noticed shell growth in oysters in the apparent absence of food. From similar observations Galtsoff ('34) reported that the amount of calcium assimilated is many times greater than could be stored in the tissues. Fox and Coe ('43) showed that in *Mytilus californianus* the amount of calcium obtained from organic food alone was not sufficient to account for the amount deposited in the shell.

In a comprehensive review of calcification in molluscs Robertson ('41) has stated that the greater part of the shell of marine molluscs is probably absorbed from sea water as calcium and bicarbonate ions. Bevelander and Benzer ('48) have shown that there is a corresponding reduction in the calcium of the growing shell, when the calcium content of sea water is reduced. In a recent study of the process of calcium intake in molluscs, Bevelander ('52) comes to the conclusion that the mollusc can and does utilize calcium in an ionic form in the production of the mineral component of the shell. Since

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[1] Contribution from the Scripps Institution of Oceanography, University of California, New Series No. 722.

[2] Present address: Andhra University, Waltair, India. Aided by a grant to Dr. Theodore H. Bullock from the National Institutes of Health, U. S. Public Health Service.

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these experiments were carried out in unfiltered sea water, they do not necessarily demonstrate the intake of ionic calcium in true solution, for it is known that large amounts of colloidally and otherwise suspended organic and inorganic matter in sea water are ingested by the filter feeders. Further, little or nothing is known about what regions of the organism may be involved in extracting the calcium from the sea water, and about the physical basis of such an intake. The belief that the primary source of calcium is that present in dissolved form is based on indirect evidence and is only inferential. The present investigation indicates that under controlled conditions a source of calcium for the shell-forming marine molluscs is found in true solution in the sea water and that it is taken up in an ionic form by a hitherto unsuspected mechanism.

We wish to express our thanks to Dr. Denis L. Fox, Division of Marine Biochemistry, Scripps Institution of Oceanography, for his encouraging interest in the present study. Our special thanks are due to Dr. Theodore H. Bullock, Department of Zoology, University of California at Los Angeles, for critically reading through the manuscript.

MATERIALS AND METHODS

Young *Mytilus californianus* Conrad, collected from the rocks at La Jolla, were kept overnight in large fingerbowls containing sea water, previously passed through a molecular filter which removed all particles larger than 0.5 μ. These bowls were kept in a constant temperature room (14° ± 1°C). Four to 7 mussels, each measuring 15 to 25 mm in length, were transferred to each of 4 fingerbowls, two of which contained filtered sea water, and the other two unfiltered sea water. One milliliter of $Ca^{45}(HCO_3)_2$ containing 101 mg of Ca^{++} with an activity of 50 μc was added to the first two and one of the remaining bowls, together containing 1500 ml of sea water; the last bowl served as a control.[3] Since normal sea water contains about 400 mg of calcium per liter, the resulting concentration of calcium in the experimental vessels was about 470 mg/l. When sea water is filtered under suction (as was the case in the present study), carbon dioxide is removed. Such a system will shift the reaction $Ca(HCO_3)_2 \rightleftarrows CaCO_3$ (ppt.) $+ H_2CO_3$ to the right. To insure such a shift, the pH of the added tracer solution was buffered to around 7.5, and during the entire course of the experiment a stream of air was kept flowing through the water in the aquaria.

The mussels were allowed to remain in the aquaria for periods of three to 36 hours. Whole animals were sectioned and radioautographs were made by the inverted autograph technique (Belanger, '50). Similar experiments were performed wherein one of the filtered sea water aquaria contained suspended colloidal graphite (Aquadag). In another case only $Ca^{45}CO_3$ was added and was kept in suspension by the aeration. In these experiments small areas were scraped away from the shell margin without injuring the soft tissues in order to induce accelerated calcium assimilation for the consequent regeneration.

Cleaned inert shell-valves as well as pieces of soft tissue were kept in experimental aquaria to serve as control references for estimating the likely exchange between active calcium of the medium and the inactive calcium of the shell or tissues.

In studying the role of mucus in other intertidal forms, freshly collected specimens of the tunicates, *Ciona intestinalis*, *Styela montereyensis*, the mussel *Mytilus edulis*, and the anemone *Anthopleura xanthogrammica* were maintained overnight in filtered sea water and then transferred to fingerbowls containing freshly filtered sea water containing the radioactive tracer. After a couple of hours, mucus collected from each animal was washed in fresh tracer-free sea water and then in distilled water. One-half milliliter of mucus was transferred to a copper planchet and dried under an infrared lamp for the assay of the radioactivity. For control purposes, mucus obtained from freshly collected members of all the above named species was washed in clean sea water and then placed for 15 minutes in filtered sea water containing the tracer. After this interval, the mucus was taken out and treated similarly for assaying of the activity.

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[3] The Ca^{45} used in this investigation was supplied by the Oak Ridge National Laboratories on allocation from the Isotopes Division, U. S. Atomic Energy Commission.

At regular intervals during the course of an experiment, individual mussels were removed from the experimental aquaria. Regions of the body were dissected away, thoroughly washed in freshly filtered sea water (without added tracer) and mounted on planchets to be dried for counting. Special attention was paid to the gills, mantle margin and transverse sections of various regions of the body. Whole animals were also mounted and dried.

Materials for sectioning were fixed in Bouin's fluid or in 10% formaldehyde, cut in paraffin and stained with basic fuchsin or Masson's trichrome stain.

RESULTS

Mytilus californianus, kept in filtered sea water with radioactive calcium ion shows a measurable intake of this cation from the medium into the tissues other than the gills within two hours, as shown by measuring the radioactivity of various parts of the body and by radioautographs of sectioned material. Gills of these animals, on the other hand, show activity within one-half to one hour in the experimental sea water. They remain the most active fraction of the body at any time thereafter. Mantle margin showed relatively high activity compared with the other parts of the mantle, but activity was highest near the regenerating region. Radioautography of sectioned material revealed extremely high concentrations of calcium in the regenerating areas of the mantle margin and these can be very sharply localized to the region of injury (fig. 1). Freehand sections (about 0.5 mm thick) of mussels three to 6 hours after the start of the experiment, passing through the body at the level of the heart, showed high activity compared to those passing through more anterior and more posterior parts of the body. The observed accumulation of active calcium in the tissues of the experimental mussels was very much greater than the total activity exhibited by dead shell and pieces of soft parts used as controls.

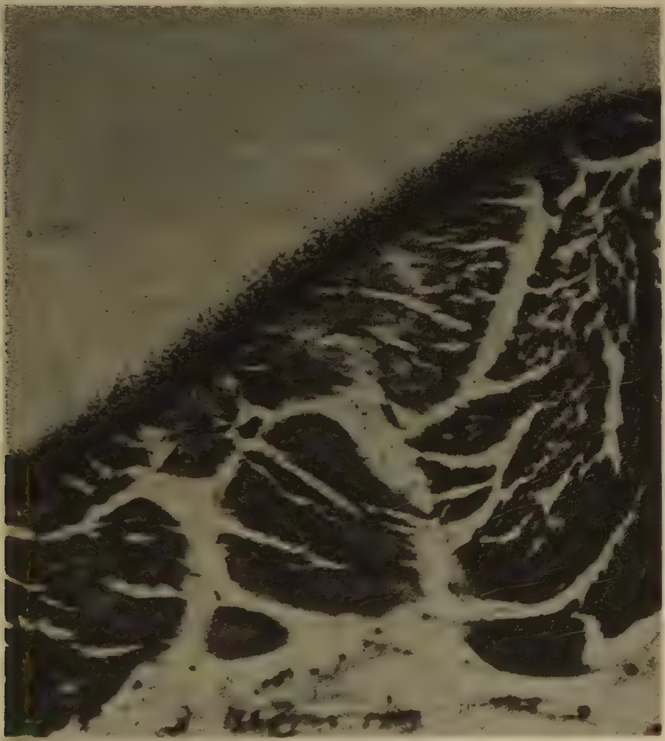

Fig. 1 Autoradiograph of the longitudinal section of the mantle margin just behind the posterior adductor in a region of repair of injury to the shell.

No detectable increase in the intake of calcium was observed in the experiments using graphite, or suspended calcium carbonate or unfiltered sea water. Thus freehand sections about 0.5 to 1 mm in thickness of such mussels after 24 hours in experimental aquaria gave 449 ± 35 counts/min., while those of mussels from filtered sea water (without any particulate material in it) gave 512 ± 37 counts/min. A slight increase in the number of counts may be noticed in the latter case. This may be due to the variables involved in such a procedure, such as the thickness of the sections and the normal variability of the counter and the disposition of the material under the end-window.

Of great interest was the fact that mucus, either *in situ* or removed from the animal, took up great concentrations of ionic calcium from solution, probably by adsorption (table 1).

TABLE 1

Uptake of radioactive calcium by mucus

(See Materials and Methods for technic)

ANIMAL	WEIGHT OF IONIC CALCIUM TAKEN UP BY MUCUS	
	In situ, exposed for several hours	Removed from body exposed for 15 mins.
	mg. Ca/ml wet wt.[1]	*mg. Ca/ml wet wt.*[1]
Ciona intestinalis	0.278 ± 0.020	0.256 ± 0.017
Styela montereyensis	0.430 ± 0.034	0.406 ± 0.031
Mytilus edulis	0.370 ± 0.025	0.352 ± 0.022

[1] Converted from activity; 5000 counts per min. represent 0.234 mg Ca^{45}.

It is significant that the mucus from different species (including non-shell forming ones) collected from about the same intertidal zone reacted in a similar manner inasmuch as it took up large amounts of ionic calcium from solution.

DISCUSSION

These experiments demonstrate that an extensive source of calcium for *Mytilus californianus* (and probably other shell-bearing marine lamellibranchs) may be found in true solution in the sea water. The amount of calcium that the animals could obtain is considerable as can be seen from the following. In these experiments about 5000 counts/min. represent 0.234 mg of calcium. Body slices of about 1 mm thickness gave about 512 counts/min., thus containing about 0.024 mg of calcium. These slices represent about one-seventh to one-tenth of the soft parts of the 15–20 mm mussels used. That means each mussel has accumulated from the medium at least 0.17 to 0.24 mg of calcium in 24 hours. According to Fox and Coe ('43) mussels of such length contain 0.156 to 0.211 mg of calcium in their tissues. Consequently, the present investigation demonstrates that calcium in true solution is taken in by *Mytilus californianus* in highly significant quantities, equivalent to more than the total content of the tissues in 24 hours and possibly much sooner in agreement with Wilbur and Jodrey ('52).

The initial transfer of calcium from the sea water to the mussel occurs at the mucus surface of the gill, perhaps by a process of adsorption, where the adsorbing surface is continuously in an unsaturated state with respect to the medium, and it is presumably maintained in such a state by a constant renewal of the surface of adsorption. In such a system the number of adsorbed ions at any given time is determined by the number present in the environment. In his review Robertson ('41) concludes that ''secretion of shell material goes on almost automatically provided sufficient calcium is available'' (of course, other conditions like temperature being within normal limits). If this be so, perhaps herein lies an explanation for the variability in shell weight encountered under different circumstances, and in different localities in the same species (Rao, '53).

The extraordinary capacity of the mucus surface in several intertidal invertebrates to adsorb ionic calcium is of interest. It has been shown by Goldberg, McBlair and Taylor ('51) that the mucus sheet of tunicates adsorbs vanadium from aqueous solution. Perhaps several ionic species are adsorbed from the medium onto the mucus surface in many marine invertebrate species. Since there are many naturally occurring glycoproteins (mucins), there are probably specific enzymes in the digestive tracts of various invertebrates capable of disintegrating the mucus and extracting only the required adsorbed components and incorporating them into their systems, the rest being thrown out. Or, in forms like the oyster, the results of Jodrey ('53) suggest that direct transfer of calcium from the mucus to the shell across the mantle margin is possible. But the exact nature of the mechanism is still unknown.

According to Fox and Coe ('43) the mussel adds shell only when in "an actively feeding condition"; if poor nutrition exists, the supply of calcium cannot be taken advantage of. Even so the present experiments show that, not only is *Mytilus* able selectively to extract calcium in solution from the sea water, but is also capable of directive localization in extremely well defined areas of the mantle where an active regeneration has been induced by scraping off tiny bits of shell-margin. This need not mean that there is any perceptible net growth taking place under our laboratory conditions. The high concentrations of calcium observed in these sites contrasts with the low concentrations reported by Jodrey ('53) in normal mantle edge.

The present results can supplement in these respects the studies of Wilbur and Jodrey ('52) and Jodrey ('53). In addition, they indicate that the 97.6% of mantle calcium which Jodrey calculates to be inactive does in fact turn over sometime within 24 hours.

SUMMARY

It has been shown that an extensive and important source of calcium for *Mytilus californianus,* and possibly other marine lamellibranchs, is dissolved in the sea water. The mucus sheet of the gills is shown to provide an adsorbing surface, which is in a constant state of renewal. Mucus of various other marine invertebrates has also been shown to behave in a similar way. Specific enzyme systems in the gut of the particular organism are believed to aid in the extraction of specific constituents adsorbed to the mucus, depending on the needs of the organism.

It has been shown that the mussel is capable of concentrating great amounts of calcium in the areas of active deposition, as in repair of local injury to the shell.

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ADDENDUM

Since the above account has gone to press, an interesting paper on strontium uptake in some molluscs and polychaetes has been published (Fretter, '53), in which some points are of interest in this connection. It was shown that in the nudibranch *Acanthodoris pilosa*, there is a relatively rapid accumulation of strontium (and presumably of calcium also) from the surrounding water. It is likely that the mucus covering over the body concentrates the ions from the medium which then pass through the general surface of the body, while "relatively few" ions are found in the lumen of the gut. In *Mytilus edulis* it was shown that strontium made a direct entry to the ciliated epithelium of the gills, although such an entry of ions into the body was not considered to be the major or primary route. It was concluded that the gut is the more important area for ingress of ions into the tissues, the ions having been directed there by the feeding currents. We have shown above that mucus is the agent by means of which ions in solution are collected from the medium and transported to the gut, this being the more important area for ingress of ions into the tissues. Entry of ions directly into the mantle tissue does occur (Hirata and Jodrey, '53), though, presumably, to a lesser degree.

FRETTER, V. 1953 Experiments with radioactive strontium (^{90}Sr) on certain molluscs and polychaetes. J. Mar. Biol. Assn. U.K., *32:* 367–386.

Seismic-Refraction Studies of Bikini and Kwajalein Atolls

By RUSSELL W. RAITT

With a section on Coordination of Seismic Data, Bikini Atoll
By BEAUREGARD PERKINS, Jr.

GEOLOGICAL SURVEY PROFESSIONAL PAPER 260-K

DEPARTMENT OF THE INTERIOR
March 3, 1849

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CONTENTS

Page
Abstract 507
Introduction 507
Acknowledgments 508
Operating procedure 508
Theory of interpretation of seismic-refraction observations 509
Travel-time plots 513
Velocities 514
  First layer 514
  Second and third layers 515
  Fourth layer 516
Velocities—Continued
  Fifth layer 516
  Sixth layer 517
Structure 517
  Interpretation 517
  Errors of interpretation 522
Discussion 523
Selected references 524
Coordination of seismic data, Bikini Atoll, by Beauregard Perkins, Jr 525
Index 527

ILLUSTRATIONS

Page
FIGURE 140. Plan of operations in the Bikini area 509
141. Plan of operations in Kwajalein Lagoon 510
142. Oscillograms illustrating bottom-refracted waves and water-borne waves 511
143. Model of subsurface structure assumed for interpretation of the travel-time plots 511
144. Travel-time plots for section through stations *A* and *B*, Bikini Lagoon 513
145. Travel-time plots for section through stations *B*, *C*, and *D*, Bikini Lagoon 513
146. Travel-time plots for section through stations *D* and *E*, Bikini Lagoon 514
147. Travel-time plots for section through stations *E*, *C*, and *A*, Bikini Lagoon 514
148. Travel-time plots for section through stations *A* and *G*, Bikini Lagoon 515
149. Travel-time plots for section through stations *J* and *J'*, Sylvania Guyot 515
150. Travel-time plots for profile extending southwest of Bikini station *J* and received at stations *J* and *J'* 516
151. Travel-time plots for section through stations *K'* and *K''* southwest of Bikini Atoll 517
152. Travel-time plots for section through stations *B*, *A*, and *A'*, extending from Bikini Lagoon into deep water 518
153. Travel-time plots for section through stations *H* and *H'* northeast of Bikini Atoll 519
154. Travel-time plots for section extending south from station *H* along the eastern side of Bikini Atoll 520
155. Travel-time plots for section through stations *A* and *B*, Kwajalein Lagoon 521
156. Hypothetical cross section of Sylvania Guyot and Bikini Atoll, through stations *J'*, *J*, *E*, *C*, and *A* 521
157. Hypothetical cross section across Bikini Atoll through stations *K''*, *K'*, *D*, *C*, *B*, *H*, and *H'* 522
158. Hypothetical cross section from Bikini Lagoon south through stations *B*, *A*, and *A'* 522
159. Hypothetical cross section of Kwajalein Lagoon through stations *A* and *B* 523
160. Variation of true velocity in third zone 526
161. Cross section of Bikini Atoll 526

BIKINI AND NEARBY ATOLLS, MARSHALL ISLANDS

SEISMIC-REFRACTION STUDIES OF BIKINI AND KWAJALEIN ATOLLS AND SYLVANIA GUYOT, 1950

By Russell W. Raitt [1]

ABSTRACT

Seismic-refraction studies made at Bikini Atoll, Sylvania Guyot, and Kwajalein Atoll on the joint University of California–U. S. Navy Electronics Laboratory Mid-Pacific Expedition of 1950 expanded the scope of the original 1946 studies to include a section across Sylvania Guyot and several deepwater sections extending from Bikini Atoll. Also Bikini Lagoon was surveyed in much greater detail, with particular emphasis on more complete control with reversed profiles. In addition, one short section was obtained at Kwajalein Atoll.

It was found that the seismic velocities beneath Bikini Lagoon vary laterally as well as with depth. They can be grouped into six more or less well defined layers averaging approximately 2.5, 3, 4, 5.5, 6.5, and 8 kmps. The first four were observed only in the lagoon profiles, and the remaining two were found only in deep water.

From sections taken on Sylvania Guyot and the flanks of Bikini Atoll near regions where samples of volcanic rock were obtained from the sea bottom, it was concluded that the third layer, of about 4 kmps seismic velocity, represents volcanic rock. Its estimated depth under Bikini Lagoon ranges from 600 m to 2,100 m and averages about 1,300 m. One short section at the south end of Kwajalein Lagoon shows somewhat greater depths of the third layer than that at Bikini Atoll but the lagoon coverage was insufficient to demonstrate that Kwajalein differs significantly from Bikini.

Indications were found that the 6.5 kmps layer is deeper under Bikini Atoll than under the surrounding deep sea. If real, this local depression is unlikely to be greater than 3 km.

INTRODUCTION

The seismic-refraction studies of 1950 in the Marshal Islands took place during the period September 29 to October 9. They formed a concluding phase of the seismic program of the joint University of California–U. S. Navy Electronics Laboratory Mid-Pacific Expedition (Revelle, foreword of chapter A, Professional Paper 260).

The previous seismic-refraction survey of Bikini in 1946 (Dobrin, Perkins and Snavely, 1949) indicated the existence of at least three layers, with velocities of the order of 7,000 fps (2.1 kmps), 11,000 fps (3.4 kmps), and 17,000 fps (5.2 kmps), respectively. The first layer, extending to a depth of 2,000 ft to 3,000 ft (0.6 to 0.9 km) was inferred to consist of calcareous lagoon and reef deposits on the basis of drilling to 2,556 ft on Bikini island in 1947.

The zone with a velocity of 17,000 fps was inferred to represent igneous basement. Its depth was indicated to be 7,000 ft to 13,000 ft (2.1 to 4.0 km). The second zone, with a velocity of 11,000 fps, was more difficult to identify. Available circumstantial evidence suggested that it was calcareous material similar to the first zone with a higher velocity caused by increasing compaction and cementation with depth. However, the possibility that it was volcanic material could not be excluded.

In planning the seismic operations within Bikini Lagoon the spacing of stations was chosen to attain an optimum degree of reversed control on the second zone. The results of the 1946 survey were very helpful in this planning.

In addition to the operations within Bikini Lagoon, an approximately equal effort was expended on operations outside the Lagoon, on Sylvania Guyot and extending down the flanks of Bikini Atoll into deep water. This work had two major objectives: (1) to seek clues for the identification of the second zone by means of outcrops and (2) to determine the relationship of the subsurface structure of Bikini Atoll and Sylvania Guyot to the structure of the deepwater region surrounding it.

A trip to Kwajalein Atoll for supplies gave an opportunity, on October 1, 1950, for one day of seismic observations in the southeast end of Kwajalein Lagoon. Although there had been no previous work on this atoll to guide this operation the principles applied to the Bikini Lagoon operation were successfully followed at Kwajalein Atoll.

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[1] Scripps Institution of Oceanography, University of California.

Note.—Contribution from the Scripps Institution of Oceanography New Series No. 723.

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ACKNOWLEDGEMENTS

Seismic-refraction operations at sea, thousands of miles from the home base, required careful planning and the cooperation of many people, whose help is gratefully acknowledged.

The work reported on was sponsored by the Bureau of Ships and the Office of Naval Research, the Institute of Geophysics of the University of California, and the U. S. Geological Survey.

Dr. Roger R. Revelle, director of Scripps Institution of Oceanography, and leader of the 1950 Mid-Pacific Expedition, was responsible for initiating the project. His infectious enthusiasm and inspiring leadership were essential to its success.

All shots were fired from USS EPCE(R)–857, whose captain, Lt. Comdr. D. J. McMillan, and officers and crew skillfully executed the difficult navigation required among the coral knolls and reefs of Bikini and Kwajalein Atolls. Major credit for the successful reception of the weak refraction signals is due to the sympathetic cooperation of Mr. James L. Faughn, captain of the receiving ship, the M. V. *Horizon*, and the officers and crew.

The friendly help of the commanding officer of Kwajalein Naval Station and his staff in supplying explosives, provisions, and fuel to the expedition was greatly appreciated.

Mr. Daniel K. Gibson supervised the shooting operations, assisted by Chief Gunner's Mate Albert Obregon, who was responsible for firing the shots. Mr. Arthur D. Raff was responsible for the receiving-equipment installation and for acquiring the vast quantity of supplies and spare parts required in its operation. In recording the seismic waves on the M. V. *Horizon* the author was assisted by Mr. T. Wayne Runyan and Mr. Jeffery D. Frautschy. The travel time data were read, plotted, and analyzed by Miss Gloria J. Slack and Miss Gwendolyn A. Roy.

Helpful discussion and criticism have been received from B. Perkins, Carl Eckart, R. S. Dietz, H. V. Menard, E. M. Hamilton, R. F. Dill, and T. A. Magness, who have read this manuscript in rough form.

OPERATING PROCEDURE

The plan of operation for the Bikini area and for Kwajalein Atoll is shown in figures 140 and 141. Points designated by letters represent receiving stations occupied by the receiving vessel, the M. V. *Horizon*, of Scripps Institution of Oceanography. At all stations within Bikini and Kwajalein Lagoons, the *Horizon* was at anchor. At all other stations the *Horizon* was either lying to or under way slowly to maintain position. Seismic shots were fired by U.S.S. EPCE(R)–857 along the solid black lines shown in figures 140 and 141. For the profiles outside the lagoons standard speed while firing was 12 knots. Inside the lagoons the risk of navigation among coral knolls required a slower speed, usually 8 knots.

With the exception of twenty 20-pound demolition charges of tetrytol obtained from Kwajalein Naval Station, all charges were made up with one-half pound TNT demolition blocks. They were fired with slow burning fuse cut to fire about a minute after ignition. Standard charge sizes of 1, 4, 20, and 50 pounds were used. The time of firing was recorded by picking up the direct blast on the firing ship's echo sounder and transmitting it by radio to the receiving ship where it was recorded by the oscillograph used to record the seismic waves.

The refracted ground waves and the direct water-borne waves were picked up by three pressure-sensitive crystal hydrophones capable of responding to sound frequencies as low as three or four cycles per second. The hydrophones were supported by buoys at a depth of 120 feet. They trailed out from the receiving ship separated by intervals of about 300 feet. It was desirable, but not always possible, to lay the line of hydrophones in the direction of the line of shots in order to obtain a rough estimate of wave velocity from a single shot. However, even when wind and current caused the hydrophone spread to make a large angle with the line of shots, the use of three separate pickups gave a great advantage in identifying a weak refracted wave in the presence of noise.

Signals from each hydrophone were recorded on a Miller oscillograph in three rather broad frequency bands centered roughly at 10, 100, and 1,000 cycles per second. Frequencies of the refracted ground wave were generally of the order of 5 to 10 cycles per second and were received only on the lowest frequency channel. The higher frequency channels recorded the water-borne waves used to determine distances between shots and hydrophones.

Timing lines were flashed on the oscillograph record at 0.01 second intervals with a slotted disc driven by a fork-controlled synchronous motor. The timing accuracy was controlled with a break-second chronometer which was checked daily with WWV time signals. Travel times of both water-borne and refracted seismic waves were read to 0.01 second. The sharp onset of refracted waves of near shots permitted the beginning to be read to this degree of precision. However, the more distant shots frequently had very gradual beginnings and the error of reading the instant of first arrival of these shots is several hundredths of a second. Figure 142 gives samples of records at various ranges inside and outside of Bikini Lagoon.

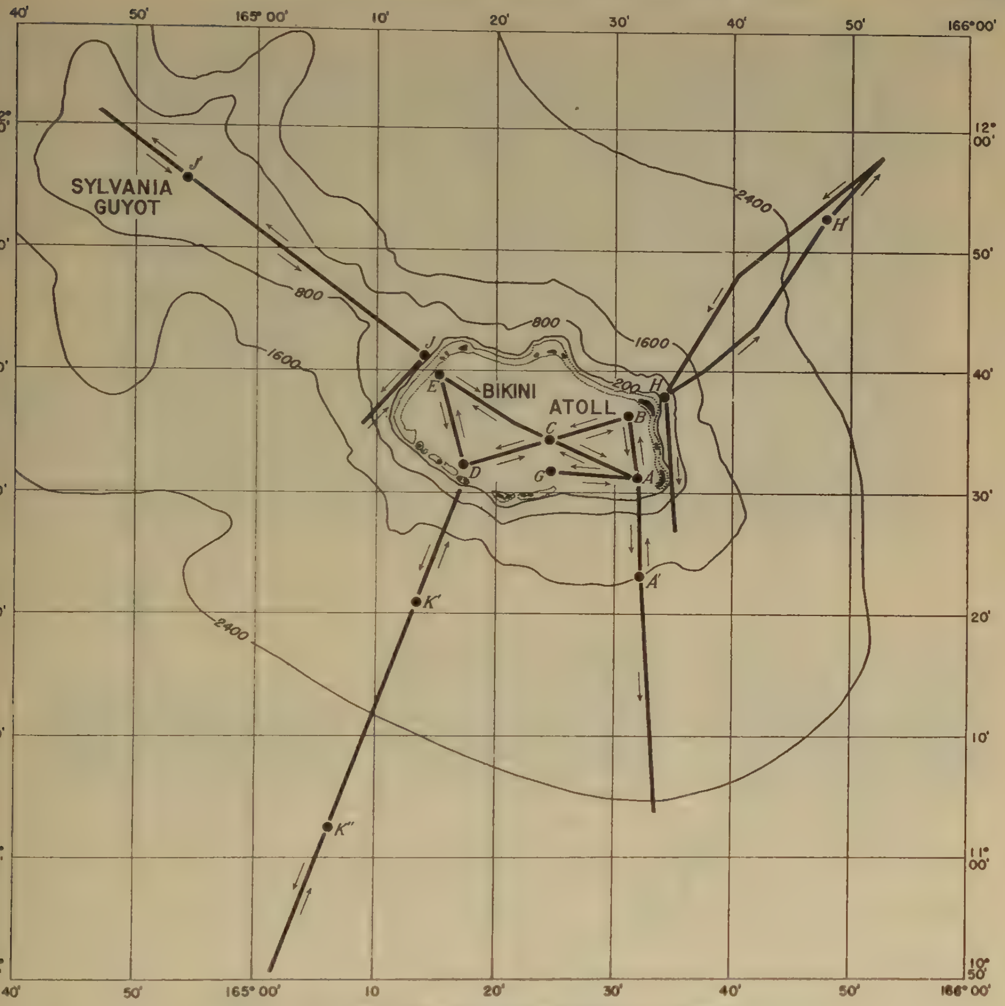

FIGURE 140.—Plan of operations in the Bikini area. Depth contours are given in fathoms.

For determining the shot-hydrophone distance from the travel time of the water-borne sound, the velocity tables of Kuwahara (1939) were used. The temperature of 29° C and salinity of 34.5 parts per thousand gave a velocity of 1.54 kmps, which was used for all the distance determinations

THEORY OF INTERPRETATION OF SEISMIC-REFRACTION OBSERVATIONS

Travel-time data for seismic waves rarely yield a unique picture of the subsurface structure. Not only is it difficult to determine the nature of subsurface rocks from measurements of seismic-wave velocity, it is also in many cases impossible to obtain a unique solution for subsurface velocity as a function of depth and position, from travel-time data alone. In most situations it is possible to set up a model of subsurface velocities consistent with the curves of observed travel time. This model may resemble the true structure to a greater or lesser degree dependent on the local conditions and on the control achieved in shooting operations.

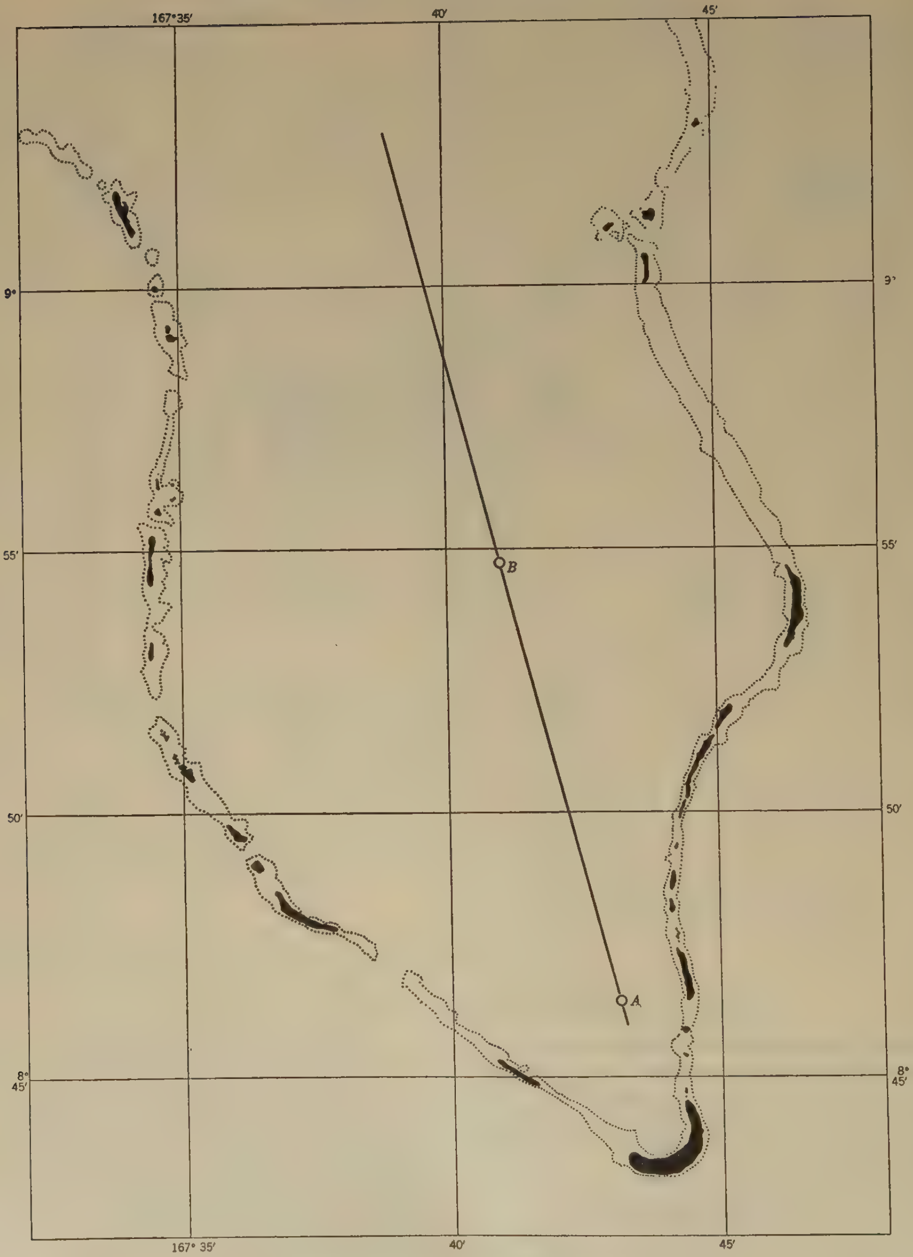
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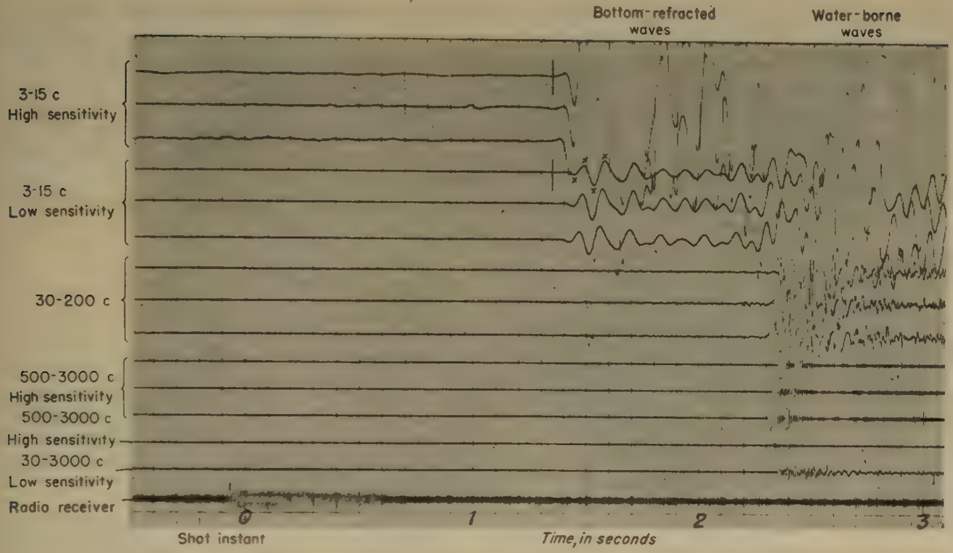
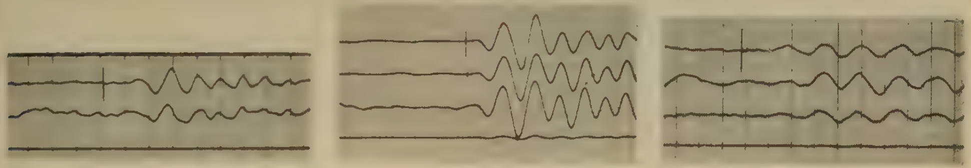
FIGURE 141.—Plan of operations in Kwajalein Lagoon.



COMPLETE RECORD OF A 1-LB CHARGE, 4.0 KM SW. OF STATION B



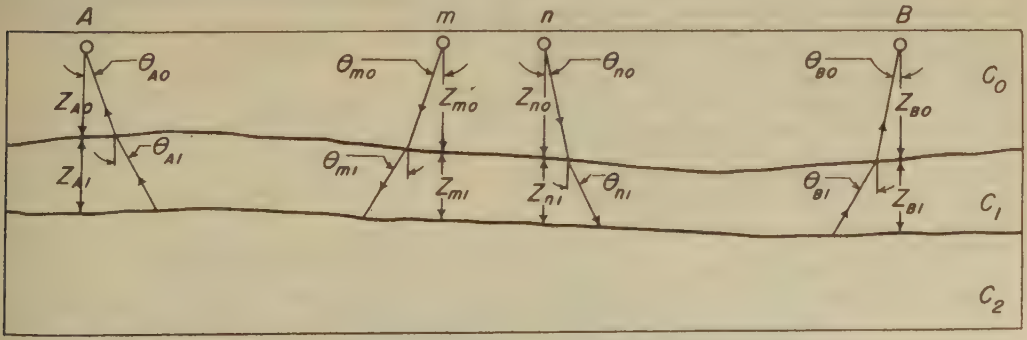
4 lbs, 34.6 km SE of Station E

20 lbs, 22.8 km SW of Station K

50 lbs, 61.0 km NW of Station J

LOW-FREQUENCY CHANNELS ONLY

FIGURE 142.—Oscillograms illustrating bottom-refracted waves and water-borne waves. In the lower three oscillograms only the first arrivals of the bottom-refracted waves are shown.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Z_{A0}
Z_{m0}
Z_{n0}
Z_{B0}
C_0
θ_{A1}
θ_{m1}
θ_{n1}
θ_{B1}
Z_{A1}
Z_{m1}
Z_{n1}
Z_{B1}
C_1
C_2

FIGURE 143.—Model of subsurface structure assumed for interpretation of the travel-time plots

The model adopted in the present survey is the conventional one, consisting of successive layers of constant velocity, with each deeper layer having an appreciably higher velocity than the one above it. This model and the interpretation methods involved in its use, have been widely discussed in the literature and in geophysics textbooks (Nettleton, 1940; Heiland, 1940); however, as the procedures used have varied somewhat, a brief discussion of the methods employed in this paper is in order.

Figure 143 illustrates a subsurface section consisting of three layers, with velocities c_0, c_1, and c_2, respectively. In seismic work at sea the upper layer is water. For the example illustrated, the velocities c_1 and c_2 are two and four times as great, respectively, as the water velocity, c_0. Two receiving stations, *A* and *B*, and two shot points, *m* and *n*, are shown. Sound rays are shown refracted through the third layer. The travel time, T_{Am}, from *m* to *A* is given by

$$T_{Am}=\frac{X_{Am}}{c_2}+\frac{z_{A0}\cos\Theta_{A0}}{c_0}+\frac{z_{m0}\cos\Theta_{m0}}{c_0}+\frac{z_{A1}\cos\Theta_{A1}}{c_1}+\frac{z_{m1}\cos\Theta_{m1}}{c_1}, \qquad (1)$$

where X_{Am} is the horizontal distance from shot to hydrophone and the *z*'s and *θ*'s have the meaning shown in figure 143. A similar equation is obtained for travel time between *n* and *B*. The term $(T_{Am}-X_{Am}/c_2)$ is called the "intercept time," (Gardner, 1939). The four remaining terms of equation (1) are called "delay times" and are designated τ_{A0}, τ_{m0}, τ_{A1}, and τ_{m1}, respectively.

In the typically deep Pacific Ocean, where the depths are of the order of 4 to 5 km, the second and third terms of equation (1), the "water delays", are each of the order of 3 seconds and are generally much larger than the delays pertaining to subsurface structure. Hence, when the topography is irregular the form of the travel-time plot is usually determined by bottom topography to a greater extent than by the underlying structure. These water delays are analogous to the familiar "weathering corrections" of seismic surveying on land. The first step in the interpretation of the data is to subtract them from the observed travel times. The resultant travel-time data, corrected for water delay, effectively represent the travel times that would have been observed if the shots and detectors had been placed on the sea bottom directly under the shot and detector positions.

In the profiles recorded in Bikini and Kwajalein Lagoons, the hydrophones and shots were placed close to the bottom, the water-delay corrections are very small, and the errors in the correction are negligible. In deep water, where the bottom is flat, the depth of shot point and receiver and the angles of incidence at the surface can be measured with precision, and the error of the water-delay correction is of the order of 0.01 second. Where the bottom slopes steeply and is irregular, such as on the flanks of Bikini Atoll, the error is greater, and can be of the order of 0.1 second or more.

After correction for water delay the corrected travel times T'_{Am} and T'_{Bn} are

$$T'_{Am}=\frac{X_{Am}}{c_2}+\tau_{A1}+\tau_{m1}$$

$$T'_{Bn}=\frac{X_{Bn}}{c_2}+\tau_{B1}+\tau_{n1}, \qquad (2)$$

The velocity c_2 can be determined from the slopes of the reverse travel-time distance profiles received at *A* and *B* from shots in the central region between *A* and *B*. For, if shot points *m* and *n* are placed at the same point, $dz_{n1}/dX_{Bn}=-(dz_{m1}/dX_{Am})$ and

$$\frac{\frac{dT'_{Am}}{dX_{Am}}+\frac{dT'_{Bn}}{dX_{Bn}}}{2}=\frac{1}{c_2}+\frac{(\cos\Theta_{m1}-\cos\Theta_{n1})\left(\frac{dz_{m1}}{dX_{Am}}\right)}{c_1}. \qquad (3)$$

For gently sloping structures (dz/dX) is small and $\cos\Theta_{m1}$ is nearly equal to $\cos\Theta_{n1}$. Hence, to a sufficient degree of approximation for nearly all cases

$$c_2=\frac{2}{\frac{dT'_{Am}}{dX_{Am}}+\frac{dT'_{Bn}}{dX_{Bn}}}. \qquad (4)$$

Also, when shots *m* and *n* are at the same point, τ_{m1} and τ_{n1} are nearly equal and may be considered so as a first approximation. If the travel time from *A* to *B* can be measured by placing a shot at *B* and receiving it at *A* or vice versa then the delay times at *A*, *m* and *B* are determined by three measured intercept times,

$$T'_{Am}-\frac{X_{Am}}{c_2}=\tau_{A1}+\tau_{m1}$$

$$T'_{Bn}-\frac{X_{Bn}}{c_2}=\tau_{B1}+\tau_{m1}$$

$$T'_{AB}-\frac{X_{AB}}{c_2}=\tau_{A1}+\tau_{B1}. \qquad (5)$$

Solution of these three equations gives the values of τ_{A1}, τ_{m1} and τ_{B1}.

The layer thicknesses z_{A1}, z_{m1}, and z_{B1} are given to a first approximation by assuming that Θ_{A1}, Θ_{m1}, Θ_{n1} and Θ_{B1} are all equal to the critical refraction angle

$\sin^{-1}(c_1/c_2)$. With this approximation,

$$z_{A1}=\frac{c_1\tau_{A1}}{\left[1-\left(\frac{c_1}{c_2}\right)^2\right]^{\frac{1}{2}}}$$

$$z_{m1}=\frac{c_1\tau_{m1}}{\left[1-\left(\frac{c_1}{c_2}\right)^2\right]^{\frac{1}{2}}}$$

$$z_{B1}=\frac{c_1\tau_{B1}}{\left[1-\left(\frac{c_1}{c_2}\right)^2\right]^{\frac{1}{2}}} \tag{6}$$

In the interpretation of travel times of waves through the c_3 layer, of higher velocity beneath the c_2 layer, corrections for delay in the c_1 layer are made in the same manner as for the water-delay correction previously described. These corrected times are then effectively those that would be observed if shots and receivers were placed on the c_1/c_2 interface directly beneath their actual positions. This requires knowledge of the velocity and thickness of the c_1 layer under all sections of the profile where penetration to the c_3 layer is achieved. The process outlined can be repeated indefinitely in principle. The practical difficulties and cumulative errors are severe if a large number of layers with small velocity contrast between them are present.

TRAVEL-TIME PLOTS

The observed travel times of the bottom-refracted waves, corrected for water delay, are plotted in figures 144 to 155. For the sections outside Bikini Atoll, where there is a great variation of bottom depth, the bottom-depth profiles are shown directly below the travel-time data.

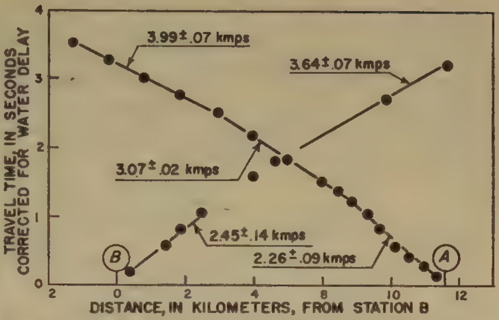

FIGURE 144.—Travel-time plots for section through stations *A* and *B*, Bikini Lagoon.

It is seen that in most of the profiles the travel-time curves can be represented by segments of straight lines. The lines drawn on the plot have been fitted by least squares to the indicated points, and the apparent velocity and standard error of its estimate are shown for each segment. Although the values of apparent velocity cover a wide range of magnitude there is a tendency to group around values of the order of 2.5, 3, 4, 5.5, 6.5, and 8 kmps, the last value being represented by a single determination at the outer end of the *K*-line southwest of the Bikini Atoll. It therefore appears that at least six velocity layers are involved in the overall structure. The first four were observed in the lagoon profiles and the last two were identified only outside Bikini Atoll.

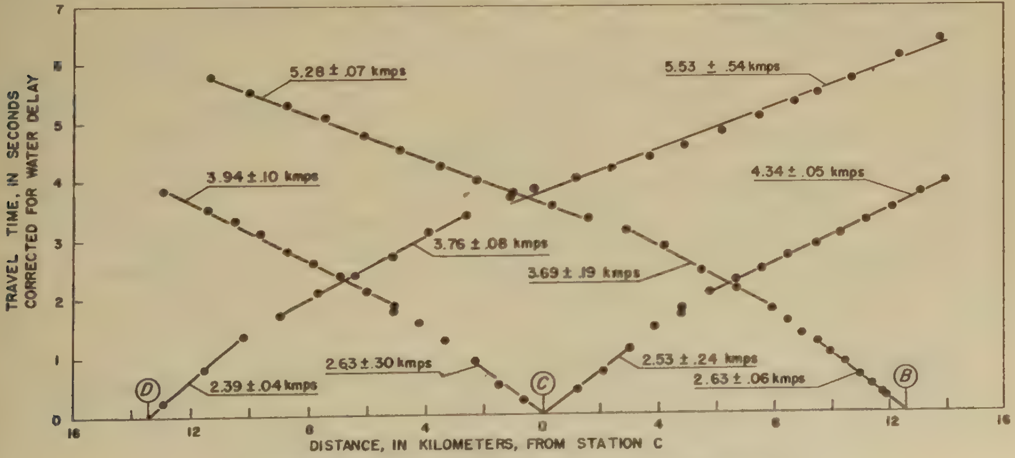

FIGURE 145.—Travel-time plots for section through stations *B*, *C*, and *D*, Bikini Lagoon.

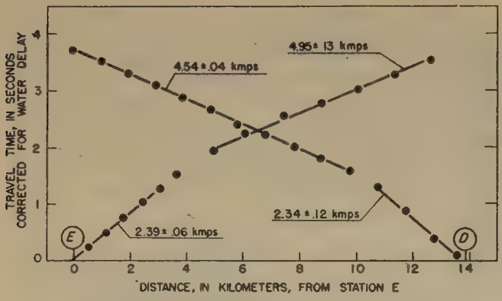

FIGURE 146.—Travel-time plots for section through stations *D* and *E*, Bikini Lagoon.

VELOCITIES

Not all the travel-time data can be used for velocity determination. Except for the initial segment of the lagoon profiles where the seismic waves were propagated through the topmost layer, the apparent velocities can be used to determine "true" velocities of the deep formations only when paired with reversed profiles in the manner of equation (4). Even though most of the lines in Bikini Lagoon, depicted in figure 140, were traversed three times by the firing ship, the distance over any one layer in which true reverse control was established was necessarily a small fraction of the whole.

FIRST LAYER

Observed only in Bikini and Kwajalein Lagoons, the velocity of the first layer was determined by using only the data of the first 3 kilometers of each profile. The waves penetrating the deeper, higher velocity layers are first observed at ranges beyond 3 kilometers; this insures that a systematic error will not be introduced by including some of these higher velocity data. Results for Bikini Lagoon are shown in table 1 and for Kwajalein Lagoon in table 2.

TABLE 1.—*First-layer velocities in Bikini Lagoon*

Station	Direction	Number of shots	Velocity (kmps)	Intercept (sec)	Harmonic mean velocity (kmps)	RMS (residuals in sec)
A	N	8	2.26±0.09	−0.034±0.034	------------	0.05
A	S	6	2.68±.16	.069±.042	------------	.05
A	W	4	2.34±.14	−.018±.050	------------	.05
A	NW	4	2.50±.24	.015±.060	2.43	.07
B	S	4	2.45±.14	.034±.038	------------	.03
B	SW	7	2.63±.06	.062±.015	2.53	.02
C	SW	3	2.63±.30	−.006±.072	------------	.05
C	NE	3	2.53±.24	−.080±.082	------------	.05
C	SE	3	2.51±.37	−.054±.113	------------	.08
C	NW	3	2.80±.19	−.019±.052	2.60	.03
D	NE	3	2.39±.04	−.002±.016	------------	.01
D	N	4	2.34±.12	−.014±.043	2.36	.05
E	S	5	2.39±.06	.025±.019	------------	.02
E	SE	7	2.36±.03	.036±.027	2.38	.01
G	E	5	2.41±.20	−.023±.065	2.41	.08

TABLE 2.—*First-layer velocities in Kwajalein Lagoon*

Station	Direction	Number of shots	Velocity (kmps)	Intercept (sec)	RMS (residuals in sec)
A	N	7	2.34±0.09	0.018±0.030	0.04
B	N	5	2.50±.15	.039±.043	.04
B	S	5	2.45±.12	.042±.037	.04

A characteristic feature of all profiles is the large scatter from linearity. The magnitudes of the residuals are much greater than the value of 0.01 sec expected at short range if the bottom were homogeneous. How-

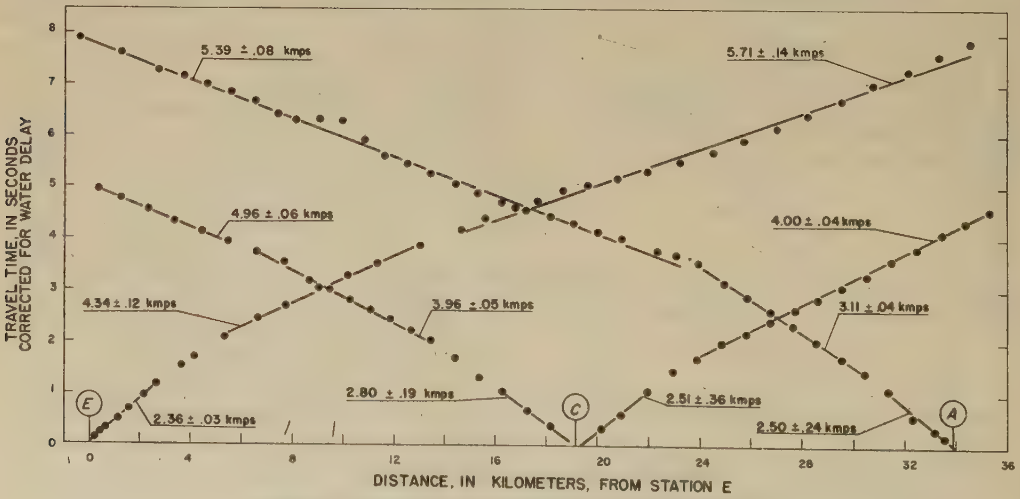

FIGURE 147.—Travel-time plots for section through stations *E*, *C*, and *A*, Bikini Lagoon.

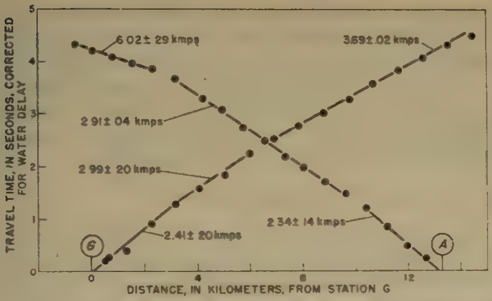

FIGURE 148.—Travel-time plots for section through stations *A* and *G*, Bikini Lagoon.

ever, they appear reasonable for a bottom formed of irregularly distributed regions of differing seismic velocity. This structure is also indicated by the irregular bottom topography, the presence of numerous coral knolls (Emery, 1948), and by the drilling under Bikini island (Ladd and others, 1948).

The highest mean velocity of any of the six stations in Bikini Lagoon was observed at station *C*, the one nearest the center of the lagoon. This effect may indicate a systematic increase of velocity from the periphery to the center. However, it is so small compared to the general variability that it may not be real. Hence, there does not appear to be any strong evidence for systematic variation of velocity of the first layer with position. The best estimate of its average velocity was taken to be the average for the six positions weighted-equally. This value is 2.45 kmps. It agrees within experimental error with the up-hole times measured in the hole drilled under Bikini island (Perkins and Lill, 1948). The velocities in Kwajalein Lagoon, tabulated in table 2, do not differ significantly from the Bikini Lagoon values.

Intercepts, with few exceptions, differ from zero by less than the standard errors. There is no positive evidence that a layer with a velocity significantly less than 2.45 kmps forms the floor of the lagoon. Failure to observe a significant intercept indicates that the 2.0 kmps (6,500 fps) layer indicated in the first survey (Dobrin, 1950) has an average thickness less than 50 m. A layer having these properties would give an intercept of 0.03 sec.

SECOND AND THIRD LAYERS

Velocities determined by equation (4) from the seven reversed profile pairs, *A–G; A–B; B–C; C–D; C–E; D–E;* and *C–A*, figures 144 to 148, ranged from 3.10 kmps for *A–G* to 4.74 kmps for *D–E*. It is concluded that velocities beneath the first layer vary with position as well as depth and that velocities 3.10 kmps and 4.74 kmps probably represent two different layers.

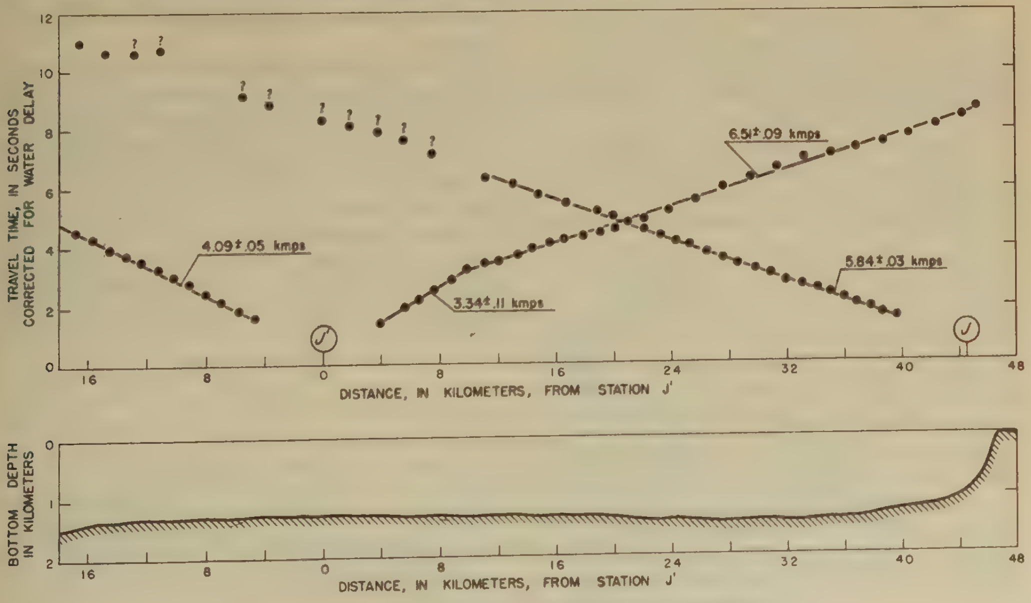

FIGURE 149.—Travel-time plots for section through stations *J* and *J'*, Sylvania Guyot.

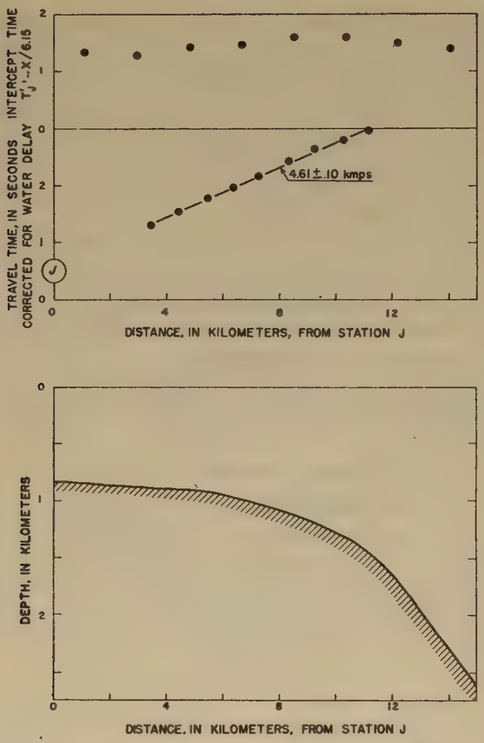

FIGURE 150.—Travel-time plots for profile extending southwest of Bikini station *J* and received at stations *J* and *J'*. The points in the upper part of the figure represent intercept times $T'_{J'}-X/6.15$ at station *J'*.

This presents a difficulty of interpretation that was also encountered by the first survey (Dobrin and others, 1949), in which an unreversed profile in the *A–G* region also showed an anomalously low apparent velocity. Although the problem presented does not have a unique solution for the available data, the solution which appears to be the simplest and most reasonable, while at the same time consistent with the travel-time data, requires two layers to include the velocity range 3.10 kmps to 4.74 kmps. The upper one, designated the second layer, is well expressed only in the reversed-profile pair *A–G* which is used to determine its velocity, 3.10 kmps. The third layer is expressed in the second segments of the reversed-profile pairs *B–C; C–D; D–E; E–C.* In these profiles the wave refracted through the second layer is suppressed entirely by the prior arrival of the waves through the third layer, or its presence is indicated only as a short transition between the first and second principal segments of the travel-time curves. The velocities of the third layer determined from these four reversed-profile pairs are: *B–C*, 3.98 kmps; *C–D*, 3.84 kmps; *D–E*, 4.74 kmps; *E–C*, 4.13 kmps. The two remaining reversed pairs, *A–B* and *A–C*, were not used for velocity determinations of the second or third layer, because of ambiguity of travel paths for these profiles.

FOURTH LAYER

Each of the long profile pairs *B–D* and *E–A* of figures 145 and 147 have outer segments whose apparent velocities average around 5.5 kmps. They are assumed to represent waves refracted through the fourth layer. Systematic departures of the travel time from the straight lines determined by least squares occasionally amount to about 0.2 to 0.3 sec. This is not an unexpected result, for it could be attributed to variations of velocity and thickness of the material above the fourth layer. A more serious anomaly is the fact that the fourth-layer velocity, determined by equation (4) in the overlap region of E–A reversed profile, varies with position along the profile. Hence, it was felt to be unsafe to base the determination of the fourth-layer velocity on the small overlapping central portion of A–E reversed-profile pair. A compromise solution adopted was to apply equation (4) to the two long segments at the ends of the reversed pair A–E. This yielded the value 5.54 kmps, which was assumed for the fourth layer throughout Bikini and Kwajalein Lagoons.

The long reversed profile pair, *J–J'*, figure 149, extending over Sylvania Guyot northwest of Bikini Atoll gives a velocity of 6.15 kmps, a value significantly greater than 5.54 kmps, but perhaps not enough greater to be regarded as a different material. Comparison of reversed slopes at individual points along the profiles shows that here too velocity varies with position. The systematic difference between the Bikini and Sylvania velocities is no greater than the differences indicated along this one section and does not necessarily indicate that the fourth layer is significantly different in the two areas.

FIFTH LAYER

In the deep-water profiles, *K'–K''*, *A–A'*, and *H–H'*, figures 151, 152, and 153, principal segments have apparent velocities of the order of 6.5 kmps, a value which indicates that this layer corresponds to that observed at all 15 deep-water areas studied in the deep Pacific Ocean basin, a layer which has an average velocity of about 6.7 kmps (Raitt, 1951). Its velocity in the Bikini area was determined from the reversed-profile pair *K'–K''* to be 6.53 kmps.

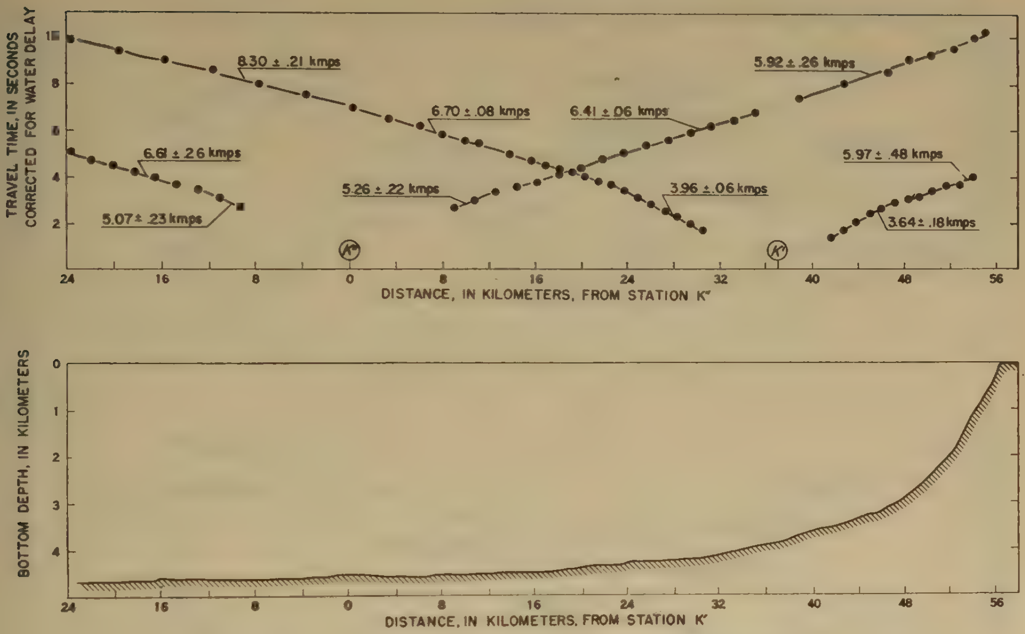

FIGURE 151.—Travel-time plots for section through stations *K'* and *K''* southwest of Bikini Atoll.

SIXTH LAYER

The outer segment of the 60-km profile extending southwest of *K'* through *K''* has an apparent velocity of 8.30±0.21 kmps. Although a reversed profile for this segment was not obtained, the fact that the short profile from station *K''* over the same area gives an apparent velocity of 6.61 kmps shows that this high velocity cannot represent a steep upward slope of the 6.53 kmps layer. Correction for the gentle slope indicated by the 6.61 kmps velocity yields a value of 8.2 km/sec for the sixth layer velocity. This agrees with values observed elsewhere in the Pacific Ocean (Raitt, 1951), and corresponds to the velocities found at the Mohorovičić discontinuity at the base of the earth's crust (Gutenberg and others, 1951).

STRUCTURE

INTERPRETATION

Depths to interfaces between the six velocity layers have been determined, using the procedure outlined in the previous section on the theory of interpretation. They are presented in figures 156 to 159, in the form of subsurface cross sections. Figure 156 represents a section extending the length of the Sylvania-Bikini axis, through stations J', J, E, C, and A. The section on figure 157 extends across Bikini Atoll from southwest to northeast and runs through stations K'', K', D, C, B, H, and H'. Figure 158 extends southerly from Bikini Lagoon through stations B, A, and A' into deep water south of Bikini Atoll. It is the only section having profiles crossing the edge of the atoll from the lagoon to deep water and vice versa. Figure 159 represents the short section observed in Kwajalein Lagoon.

In each figure the stippled portions of the interfaces represent sections along which shots have been received with velocities corresponding to strata just below the stippled interface. The dashed interfaces have been assumed in order to calculate the depth to deeper strata.

The velocities used in calculating the layer thicknesses are shown on the sections. In sections where the velocity was not directly measured, assumed values based on apparent velocities and measurements of the same strata elsewhere were used. Wherever this was done, the assumed values are enclosed in parentheses.

For example, at station *K'* the initial segment represents the material at or near the bottom surface. Its velocity, determined by averaging the two profiles, was determined to be 3.79 kmps, a value corresponding to that of the third layer. In the other deep-water

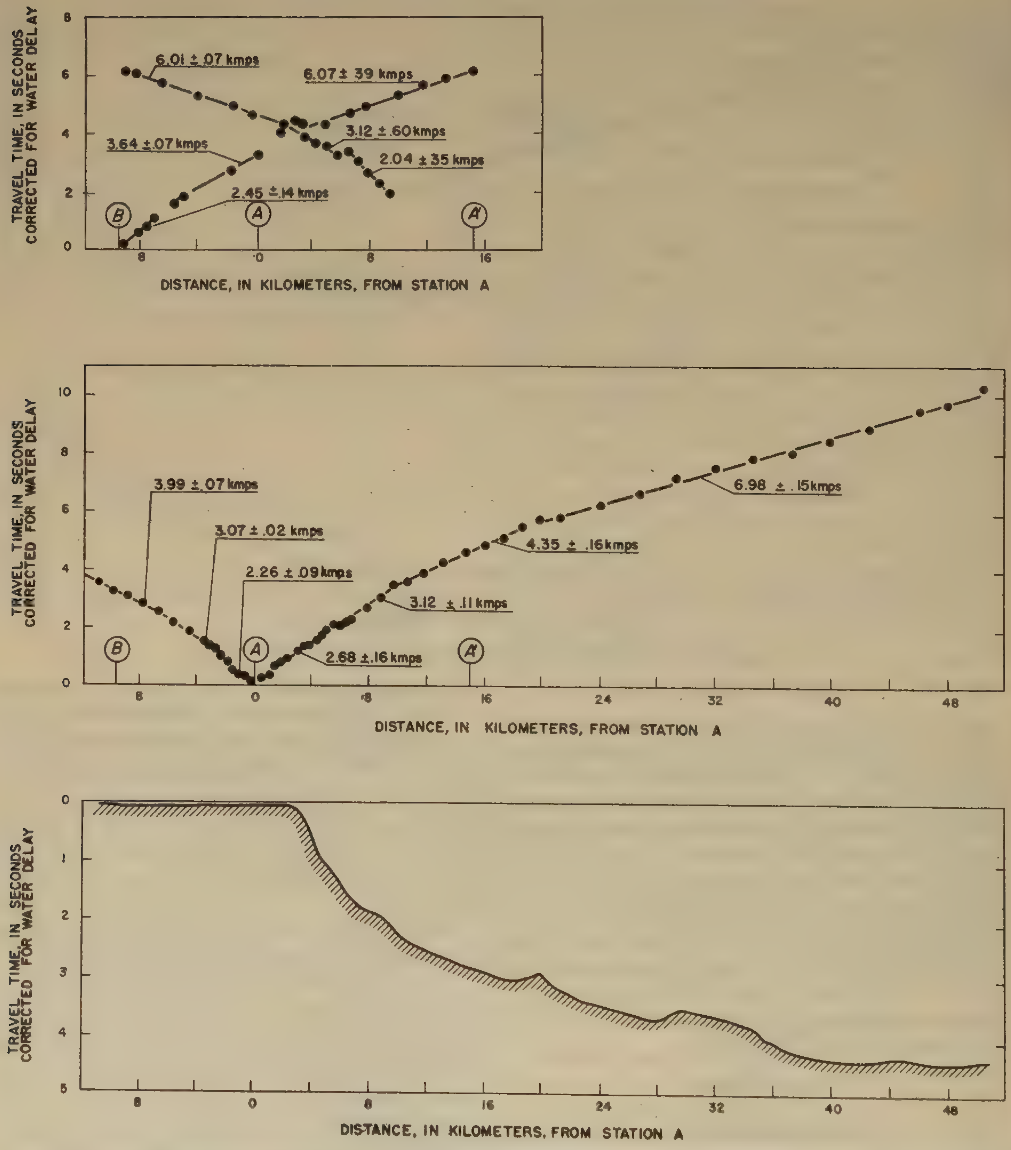

FIGURE 152.—Travel-time plots for section through stations *B*, *A*, and *A'*, extending from Bikini Lagoon into deep water south of the atoll. The data previously shown in figure 144 are repeated for comparison.

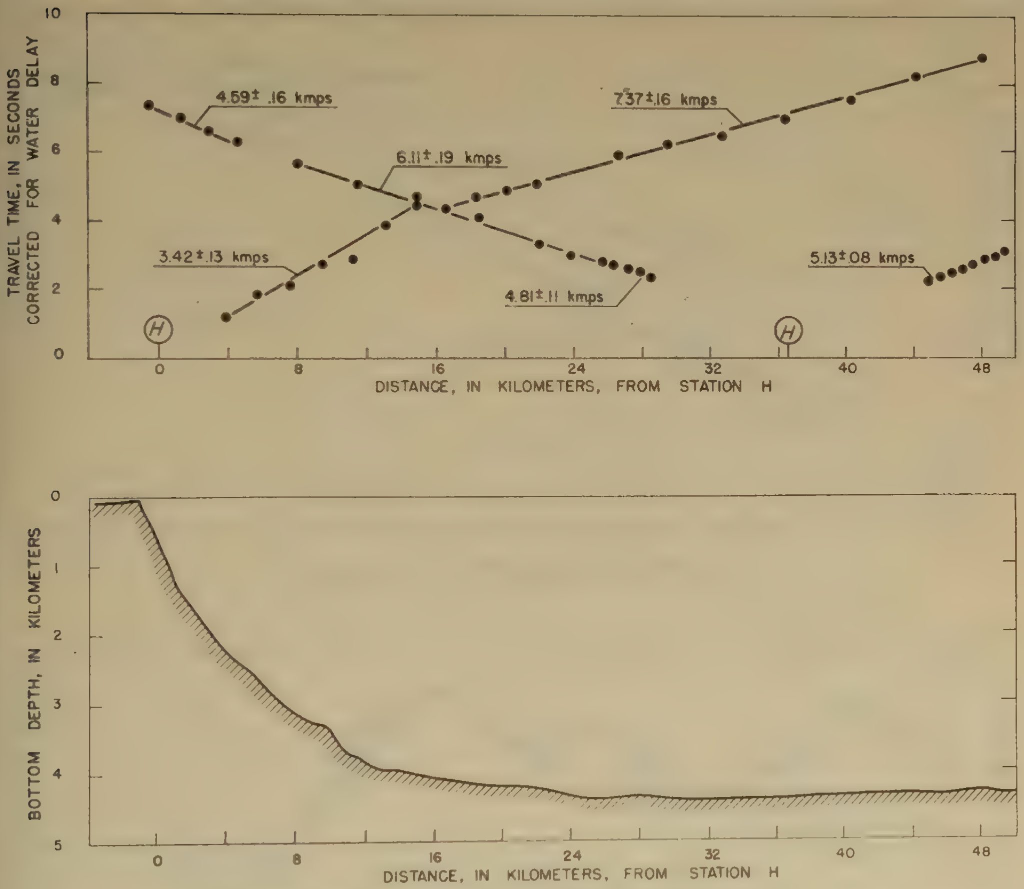

FIGURE 153.—Travel-time plots for section through stations *H* and *H′* northeast of Bikini Atoll.

cross sections, however, the velocity of the layer exposed at the bottom was not determined. Hence, 6.79 kmps was assumed for the upper layer of the lower slopes of the atoll in profiles *H—H′* and *A—A′*.

In deep water well away from Bikini Atoll, where the bottom is flat, sediment is being deposited and the velocity is lower. The value 3.0 kmps was assumed to be reasonable in this area for the average value of the upper layer.

Owing to the fragmentary nature of the subsurface control, the horizontal variation of velocity, and the great changes of depth in the subsurface structure, the cross sections shown are necessarily highly schematic. No attempt was made to compute depths shot by shot for each of the 617 shots of the survey. Depths were computed at the receiving station and at a few control points between stations. Interfaces between between these points were then sketched in with reference to the travel-time data. This procedure yields a hypothetical structure whose calculated travel times agree on the average within about 0.1 sec with the observed travel time. It tends to give some smoothing of the interfaces because there is no way of separating the relative effects of velocity changes and topographic roughness in producing minor irregularities of travel time. However, this does not mean that the seismic interpretation always tends to show a reduction in the magnitude of the relief. An illustration of the reverse is the sharp change of depth to the fourth layer between stations *E* and *J*, which is probably an interpretation

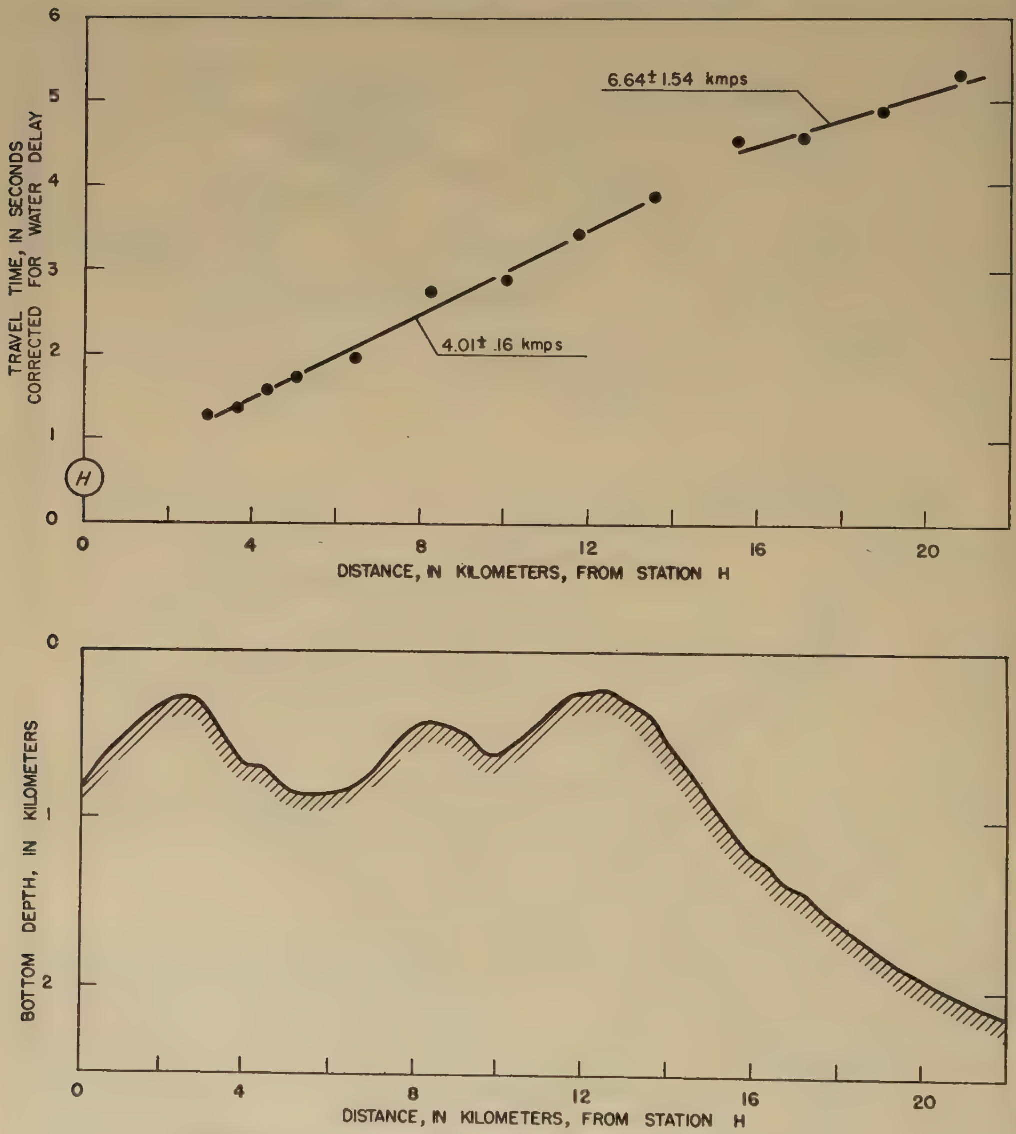

FIGURE 154.—Travel-time plot for section extending south from station *H* along the eastern side of Bikini Atoll.

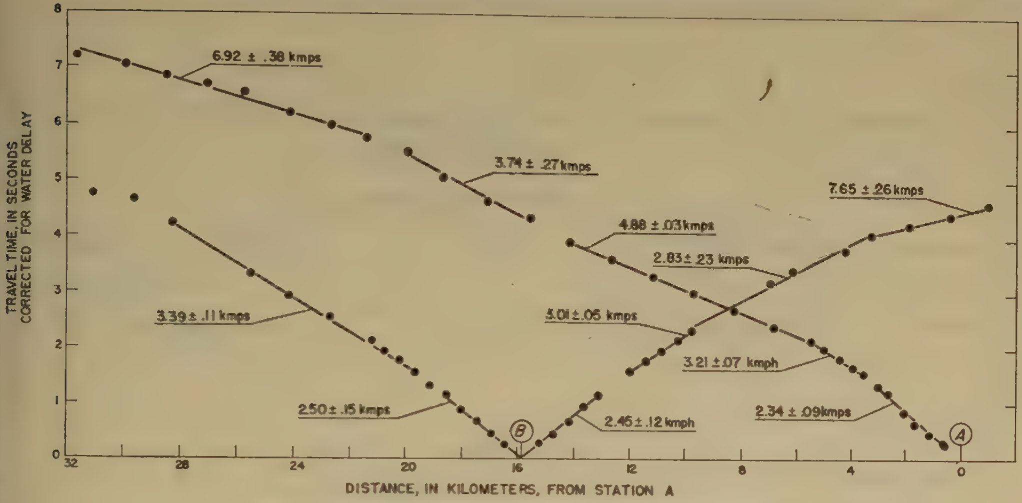

FIGURE 155.—Travel-time plots for section through stations *A* and *B*, Kwajalein Atoll.

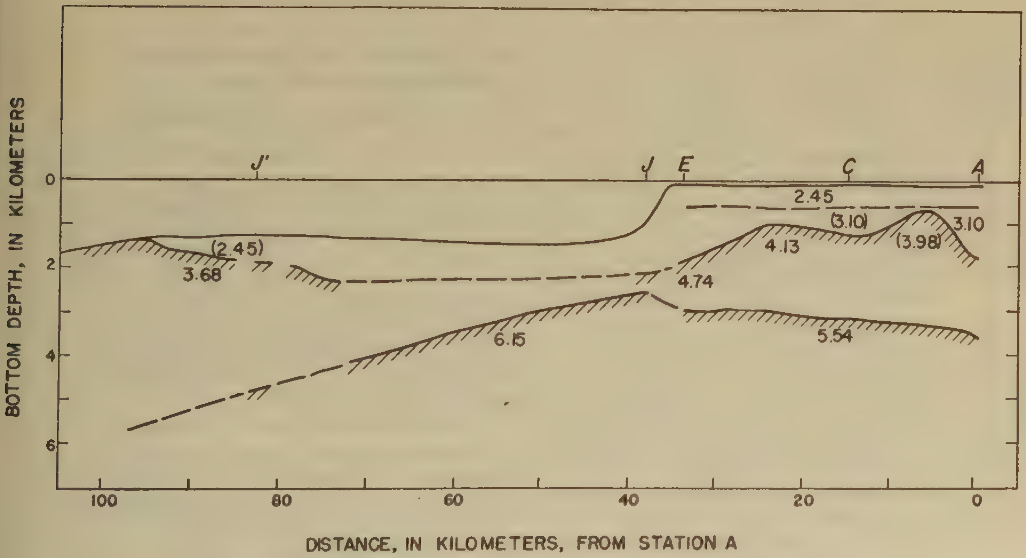
BOTTOM DEPTH, IN KILOMETERS
0
2
4
6
J'
J
E
C
A
2.45
(3.10)
3.10
(3.98)
4.13
(2.45)
3.68
4.74
6.15
5.54
100
80
60
40
20
0
DISTANCE, IN KILOMETERS, FROM STATION A

FIGURE 156.—Hypothetical cross section of Sylvania Guyot and Bikini Atoll through stations *J'*, *J*, *E*, *C*, and *A*.

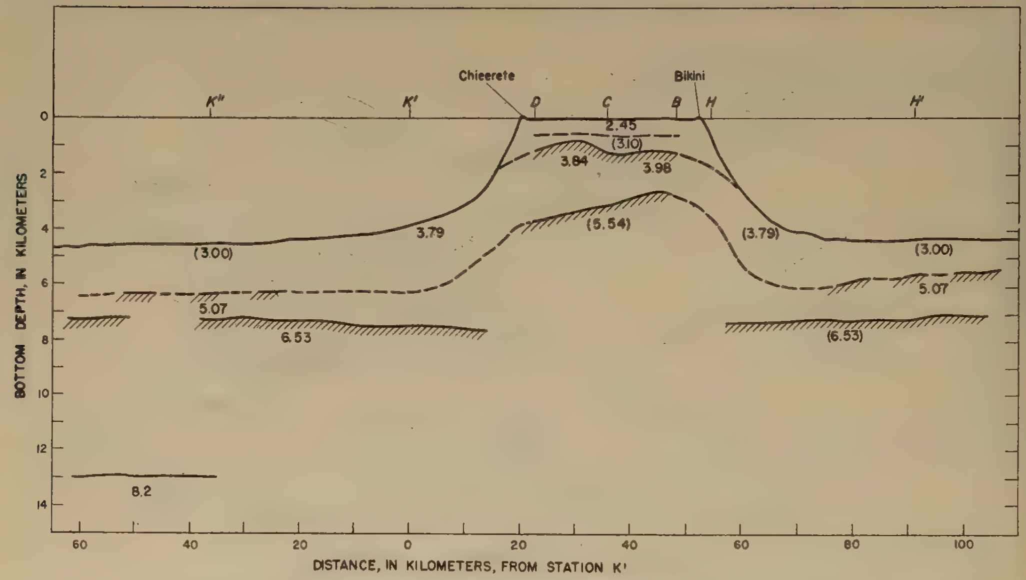
Chieerete
Bikini
K''
K'
D
C
B
H
H'
2.45
(3.10)
3.84
3.98
3.79
(5.54)
(3.79)
(3.00)
(3.00)
5.07
5.07
6.53
(6.53)
8.2
BOTTOM DEPTH, IN KILOMETERS
0
2
4
6
8
10
12
14
60
40
20
0
20
40
60
80
100
DISTANCE, IN KILOMETERS, FROM STATION K'

FIGURE 157.—Hypothetical cross section across Bikini Atoll through stations *K''*, *K'*, *D*, *C*, *B*, *H*, and *H'*.

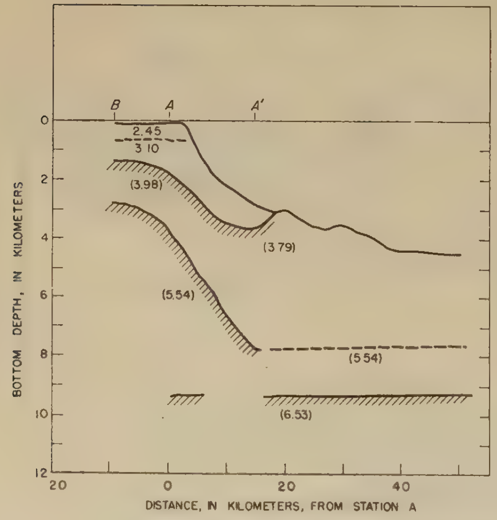
B
A
A'
2.45
3.10
(3.98)
(3.79)
(5.54)
(5.54)
(6.53)
BOTTOM DEPTH, IN KILOMETERS
0
2
4
6
8
10
12
20
0
20
40
DISTANCE, IN KILOMETERS, FROM STATION A

FIGURE 158.—Hypothetical cross section from Bikini Lagoon south through stations *B*, *A*, and *A'*.

error caused by the arbitrary change of assumed velocity between stations *E* and *J*.

ERRORS OF INTERPRETATION

Although it is clear that other structure sections differing from those of figures 156 to 159 may agree reasonably well with the travel-time data, it is not clear how great a permitted variation from these sections can be. There are many factors affecting the error of depth of measurement and they operate in varying degree in different regions of the survey. In general, they can be lumped into three categories: (1) errors of measurement of the travel time; (2) errors of velocity, and (3) errors in the interpretation of the path traveled by the refracted wave.

Errors in category (1) have been discussed in previous sections and are rarely greater than 0.10 sec. Errors in category (2) depend not only on the accuracy of the velocities of the material through which the waves can travel but also on the path length. Hence, they are greater for distant shots and deep layers and may amount effectively to several tenths of seconds, particularly for cases having poor velocity control.

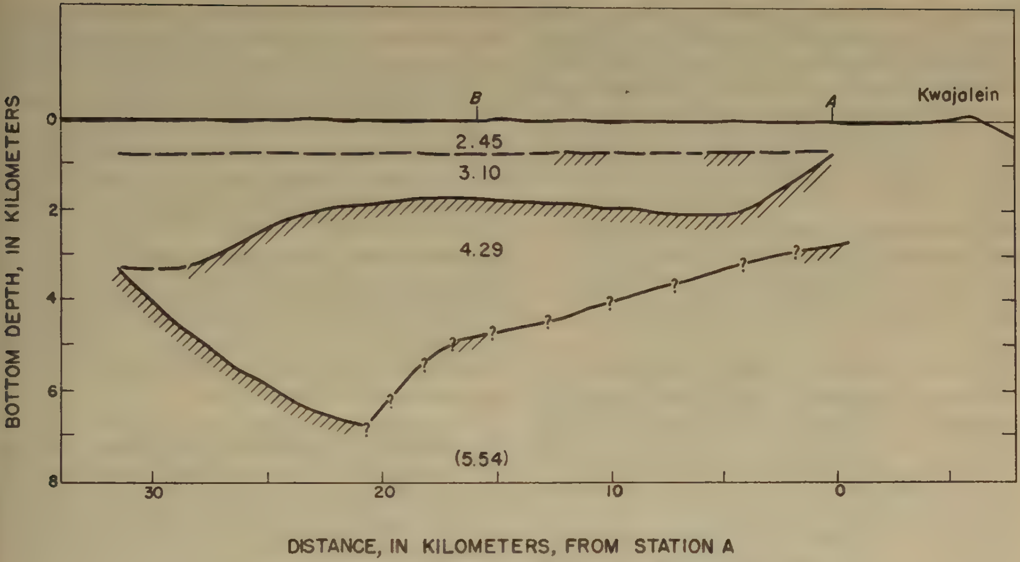
BOTTOM DEPTH, IN KILOMETERS
0
2
4
6
8
B
A
Kwajalein
2.45
3.10
4.29
(5.54)
30
20
10
0
DISTANCE, IN KILOMETERS, FROM STATION A

FIGURE 159.—Hypothetical cross section of Kwajalein Lagoon through stations *A* and *B*.

Category (3) is the most difficult to specify because it involves departures of the true structure from the assumed model in a manner which cannot be determined from travel-time data alone. It is probably least important for the Bikini Lagoon profiles, where the detailed shot pattern provides the most complete control.

The greatest uncertainty in this category occurs in those portions of the three deep-water cross sections *A–A′*, *K′–K″*, and *H–H′* which lie under the steep flanks of Bikini Atoll. Travel-time data are insufficient to determine the continuity of interfaces between the lagoon and deep water outside. This is to a great extent a fundamental indeterminancy in this complex type of structure, which is far from the "ideal" simple situation required for a unique solution (Nettleton, 1940, p. 255). In addition, it is aggravated by sparse velocity control.

Although the nebulous character of the errors in category (3) renders a precise statement impracticable, reasonable estimates of the depth errors would allow the order of 100 m to 200 m for the shallower strata under Bikini and Kwajalein Lagoons and as much as 3 km for the 6.53 kmps layer under the flanks of Bikini Atoll. In the relatively horizontal structures in deep water far from Bikini Atoll and in the deep layers beneath Bikini Lagoon and Sylvania Guyot the depths may be in error by the order of ½ km to 1 km.

DISCUSSION

Even though many details are missing and much of the picture is subject to considerable uncertainty, most of the major features of the subsurface structure of Bikini Atoll and Sylvania Guyot are shown by the seismic cross sections. The geological significance of all of these features requires detailed study of the palaeontology and petrology of the bottom samples and the deep boring in the Bikini area and throughout the Marshall Islands as well. Other pertinent geophysical data such as the magnetic studies of Aldredge and Dichtel (1949) should also be considered.

The coordination of this great and complex quantity of observations is beyond the scope of this report and has been treated elsewhere (Emery, Tracey, and Ladd, 1954). However, it is appropriate to close with a discussion of the most significant contributions of the 1950 seismic studies to this problem. These involve two principal aspects: (1) the form of the ancient volcano now buried by calcareous deposits and (2) the local distortion of the crust accompanying the formation of a guyot and an atoll.

Regarding the first aspect, it now appears probable that the third layer, whose velocity is of the order of 4 kmps, represents volcanic rock. There are little data in the literature (Birch, 1942; Gutenberg, 1951) to support this conclusion. Some data on basalt

(Brockamp and Wolcken, 1929) give 5.6 kmps, which is about that observed for the fourth layer. However, this probably represents plateau basalt, whose elastic moduli are expected to be higher than for lavas and pyroclastic deposits forming a volcano. That velocities of volcanic rock of Pacific islands are variable and of the order of 4 kmps is shown by unpublished observations by the writer in shallow water off the northeast coast of Hawaii Island. Reversed profiles in this area indicated that velocities of the upper layers are variable and of the order of 3 to 4 kmps. Velocities of the order of 6 kmps were found only at depths of at least 2 km. Similar results were found at Guadalupe Island, a recent extinct volcano off the coast of Mexico.

Two seismic refraction studies have been made near Bermuda, an island which a deep boring has shown to be composed of volcanic rock below about 250 ft subsea (Pirsson and Vaughan, 1913; Pirsson, 1914; Sayles, 1931). Seismic velocity determined by Woollard and Ewing (1934) was 4.9 kmps and by Gaskell and Swallow (1951) was 4.1 kmps.

Furthermore the variability of velocity observed for the third layer is quite reasonably explained in terms of the great variability of physical structure of the various types of rock emitted in volcanic eruption. On the other hand, the variations in velocity and topography in the third layer are unreasonable for a structure formed of an orderly succession of calcareous shallow-water deposits similar to those now being laid down in view of the absence of any systematic variation of velocity of the first layer in Bikini Lagoon.

Direct evidence for the identification of the third layer as volcanic is found in the presence of volcanic rocks on Sylvania Guyot and on the southern slopes of Bikini Atoll, (Emery, Tracey, and Ladd, 1954). In both areas the seismic data indicate that the third layer crops out. However, on the guyot the outcrop is indicated only at the northwest end. Although velocity control is incomplete much of the guyot appears to be covered with a layer of undertermined velocity significantly less than 3.68 km/sec. This layer may be largely composed of calcareous sand, but it may also contain a high proportion of volcanic sand and gravel similar to that found below the calcareous deposits in the deep boring of Bermuda Island.

Beneath Bikini Lagoon the depth of the third layer averages about 1.3 km, closely approximating the average depth of Sylvania Guyot. Its relief is considerable, being of the order of 1½ km from greatest to least calculated depth. The highest point determined in the survey was found about two-thirds of the distance from station *C* to station *A* where its estimated depth is 0.6 km. At the periphery of the lagoon the depths are systematically greater. Although no depth determinations were made under the islands of Bikini Atoll rough estimates from interpolation on the *K''* to *H'* cross sections of figure 157 indicates that the depth under Chieerete and Bikini islands is about 1.5 km.

The short section under Kwajalein Lagoon shown in figure 159 exhibits the same principal features as the Bikini sections. Although minor differences are apparent there is no basis for concluding that Kwajalein differs significantly in subsurface structure from Bikini.

Regarding the second major aspect—the local depression of the crust beneath Bikini—the sections of the profile of greatest interest are also those having the greatest error of depth determination—that is, the sections running from deep water to the lagoon. Hence, any conclusion concerning them must be qualified by this uncertainty.

If it is assumed that prior to the beginning of the volcanic eruption the fifth layer, of 6.53 kmps velocity, was approximately flat in the Bikini region, then the eruption should be accompanied by a down-warping of the crust in order to fill the void that would otherwise be created by the withdrawal of the material erupted. The magnitude of the depression of the crust will depend on such factors as the densities of the volcanic rock and of the magma from which it is derived, the degree of isostatic compensation, and the depth from which the erupting rock is derived. One of the key problems in the study of the mechanics of volcanic eruption and the related problem of the yielding of the earth's crust, is to know whether or not this depression takes place locally under the volcano or is regionally distributed (see, for example, Daly, 1942; Vening Meinesz, 1941; Woollard, 1951).

From the illustrated cross sections the evidence appears to favor a depression of the 6.53 kmps layer. It is only slightly indicated in the *H–H'* and *K'–K''* profiles, and amounts to about 2½ km for the *A–A'* section. This is of the same order of magnitude as the estimated-depth error and can hardly be regarded as significant without further work supporting it. Hence, it is concluded that if there is a local depression of the crust it is less than 3 km.

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COORDINATION OF SEISMIC DATA, BIKINI ATOLL

By Beauregard Perkins, Jr.

The two seismic surveys of Bikini Atoll differed greatly in character. The survey of 1946, which was reconnaisance, provided velocity information of the various horizons at only a few points. It was without reverse control except on one profile and then only for the deepest horizon. The 1950 survey, on the other hand, provided excellent velocity control and added much detail to the subsurface picture. The first survey provided velocity information of the first and second zone at only two points in the lagoon, one at Enyu island and the second at Yurochi island. Of these two locations only the first corresponds in location to profiles of the second survey. The first survey being so sketchy, several pictures of the subsurface could be fitted to the data, and actually three possible pictures were proposed. Only general features of the results of the two surveys can be expected to match.

The following general features are shown by both surveys:

a. A surface zone of uniform thickness.
b. The basement (velocity 5.54 kmps) rises from Enyu toward the northwest.
c. An anomalous velocity situation exists in the southeast corner of the lagoon.

In the vicinity of Enyu island where the velocity in zones 1 and 2 were determined in both surveys, the agreement was very good. In the first survey along the Enyu-Chieerete profile the velocity of the second zone was 2.74 kmps.

This is in good agreement with 2.95 kmps, the average of the velocities of the second zone, shown in figure 148, in the second survey, or in reasonable agreement with Raitt's calculated value of 3.10 kmps. The velocity of 3.35 kmps for the second zone near Enyu on the Enyu-Namu profile in the first survey agrees with the velocity of 3.35 kmps for the same zone along profile A–B and compares favorably with the velocity of 3.56 kmps along profile *A–C* in the second survey.

The velocities determined inside the lagoon in the two surveys were:

Zone	Velocities in kmps—		Nature of zone
	1st survey	2d survey	
First	2.1	2.45	Calcareous.
Second	2.74 3.35	2.95 3.35	Assumed calcareous.
Third	------	3.56 4.15 4.74	Assumed volcanic material.
Fourth	5.2	5.54	Assumed basement.

Velocities of 3.56 kmps to 4.74 kmps were not detected in the first survey. The value 5.2 kmps for the deepest horizon of the first paper is probably the average of the velocities of the third and fourth zones as defined by Raitt.

An areal plot (figure 160) of Raitt's average velocity of the third zone within the lagoon shows an increase in velocity from the southeast corner of the lagoon toward the north and west. This indicates a change in elastic properties of the material composing this third zone from southeast to northwest. The magnetic map (Alldredge, L. R., and Dichtel, W. J., 1949, Interpretation of Bikini magnetic data: Am. Geophys. Union Trans., v. 30, p. 831–835) shows sharply defined areas of various degrees of intensity. The intensities

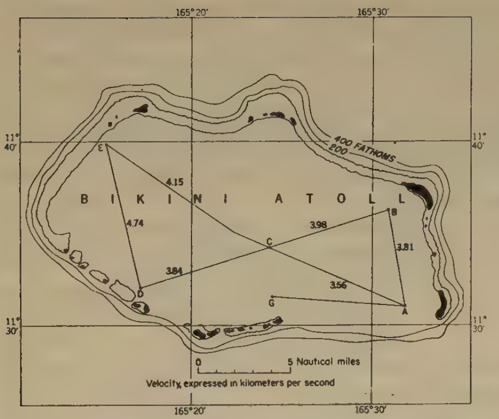
165°20'
165°30'
11° 40'
11° 30'
400 FATHOMS
200
B I K I N I A T O L L
E
4.15
4.74
3.98
B
C
3.81
3.84
3.56
D
G
A
0 5 Nautical miles
Velocity, expressed in kilometers per second

FIGURE 160.—Variation of true velocity in third zone showing gradual increase from southeast to northwest. Average velocities calculated from profiles of second survey.

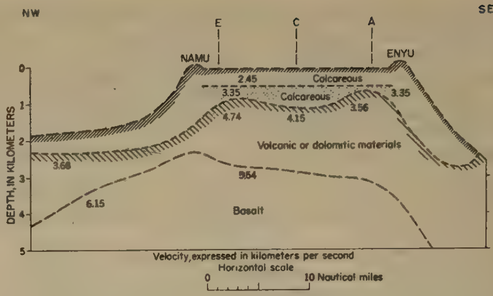
NW
SE
E
C
A
NAMU
ENYU
DEPTH, IN KILOMETERS
0
1
2
3
4
5
2.45
Calcareous
3.35
Calcareous
3.35
3.56
4.74
4.15
Volcanic or dolomitic materials
3.68
5.54
6.15
Basalt
Velocity, expressed in kilometers per second
Horizontal scale
0 10 Nautical miles

FIGURE 161.—Cross section of Bikini Atoll showing zones of different seismic velocity and the change in velocity in the third zone from the vicinity of Enyu on the south east to the vicinity of Namu on the northwest, based on data of first and second surveys.

increase to the north and west in a similar fashion to the velocities. This is probably due to a change in magnetic properties of the rock, since the relief of the top of the third zone does not match the sharp changes indicated by the magnetic map. These changes indicate the possibility of the third zone being composed of volcanic material. The possibility of this zone being composed of dolomitized limestone cannot be ruled out, however, since the velocity change can be due to different degrees of dolomitization and the magnetic changes may be due to conditions in the basement. Figure 161 is a cross section of Bikini Atoll which incorporates all the above features.

INDEX

Page

Abstract 507
Angles of incidence, measurement 512
Anomalous velocity situation 516, 525
Atoll, Bikini 507, 512, 524

Basement rock, igneous 507
  rise to northwest 525

Chronometer 508, 512
Critical angle 512
Cross section, Bikini island and Sylvania Guyot 521
  hypothetical, Bikini 523
    Kwajalein 523

Delay corrections, in second layer 513
Delay times 512
Difficulties, interpretation of travel time 509

Enyu island 525
Errors 509
  in correction, magnitude 512
  in estimate of depth 523
  in interpretation 522–523

Fifth layer, depression of 524
  velocities in 516
Fourth layer, velocities 516
Frequency, ground waves 508

Ground Waves, refracted 508

Hydrophones, recording 508

Igneous rock 507
Intercept times, equation 512

Lagoon, Bikini 507, 512, 515
  Kwajalein 512, 515, 524
Layers, of constant velocity 510, 513
  of different velocity 507
  thickness equation 513

Mohorovičić discontinuity 517

Objectives 508
Oscillograms 510

Page

Oscillograph 508
Outcrops 507

Plan of operations 508
Precision, degree, travel time 508

Recording, time of shots 508
Residuals 514–515

Sea floor, shape, influence on travel time 512
Second layer, velocity 507
Seismic-refraction studies 507
Shots 508
  course for 508
  explosive charges 508
  firing ship 508
  recording time of 508
  speed of taking 510
Sixth layer 517
Spacing, hydrophones 508
Stations, spacing 507
Structure 507
Subsurface structure, model 511, 512
Subsurface velocities, model 509
Surface zone 525
Survey of 1946 507
Surveys of 1946 and 1950, compared 524
  common conclusions 524
Sylvania Guyot 507, 516
Systematic increase, velocity 515

Third layer, average depth to 524
  not of sedimentary origin 524
  relief 524
  velocity 516
  velocity equation 515
  velocity variations, explanation 525
Time of studies 507
Timing, shots 508
Travel time 508, 509
  equations 512
  plots 513-521
  standard error 521

Water delays 512

Yurochi island 512

Reprinted from The Condor, Volume 56, July–August, 1954, Number 4, p. 228

Western Gull, with Symmetrical Wing Patches, Resembling Aberrant Heermann Gulls.—While and since making observations on the persistence of a rare color aberration in the Heermann Gull (*Larus heermanni*), I have seen, in the general vicinity of San Diego, California, a considerable number of Western Gulls (*Larus occidentalis*) that showed a more or less definite white blotch at the angle along the front of each wing. Usually these symmetrically paired markings were small and irregular and I never could feel quite certain that the peculiarity was not due to displacement of wing coverts or to molting rather than to an aberration in pattern. On December 11, 1953, however, while on a cruise of the M. V. "Horizon," about four miles off the Whistling Buoy near the entrance to San Diego Harbor, I observed for some time at close range (to within 50 feet), with binoculars, from above as well as from the side, a fully adult Western Gull that was unquestionably aberrant in this respect. The approximate size and position of the very definite white areas was indicated on a field sketch, a copy of which is reproduced as figure 1. The aberration is noteworthy not only for its symmetry but also for its resemblance to the color variant noted in the Heermann Gull by several authors (Hubbs and Bartholomew, Condor, 53, 1951:221-227, with references; Pursill and Williams, Condor, 54, 1952:114-115).—Carl L. Hubbs, *Scripps Institution of Oceanography, University of California, La Jolla, California, January 1, 1954.* Contribution from Scripps Institution of Oceanography, new series no. 724.

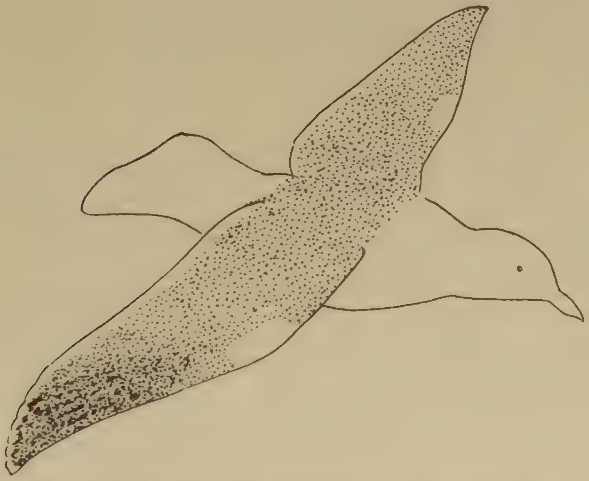

Fig. 1. An adult Western Gull sketched to show position of symmetrical white patches on angles of the wings.

Reproduced, by permission, from Condor, v.56, no.4, 1954.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 24, NO. 3, PP. 151–158
FIGS. 1–8, SEPTEMBER, 1954

NOMENCLATURE BASED ON SAND-SILT-CLAY RATIOS[1]

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ABSTRACT

Following a canvassing of sedimentationists an attempt is made to standardize nomenclature of sediment types relative to sand, silt, and clay content. A triangle diagram with boundaries between types, which met with general approval, is submitted and compared with other systems which have been used for the purpose. The new system uses old well established names and has a simplicity and symmetry which make it easily remembered. The boundaries appear to be well located for description of sediments such as those that have been analyzed in large volume from the investigations of the northern Gulf of Mexico (API Project 51), but it is inadequate in describing well sorted sediments with median diameters near the boundaries of sand and silt or silt and clay. The nomenclature suggested applies only to sediment grade sizes so that other names should be used depending on other characteristics of the sediments. Furthermore, the nomenclature should not be applied to sediments containing large percentages of gravel.

INTRODUCTION

The adequate description of sediments should be based on many characteristics of which the sand-silt-clay ratios are only one. It is important, however, to develop an adequate nomenclature relative to these sediment constituents. Among American geologists definitions of sand, silt, and clay have become essentially standardized with an arbitrary demarcation line based on median diameter at 1/256 mm. (3.9 microns) between clay and silt,[2] and at 1/16 mm. (62.5 microns) between silt and sand. Most typical clastic sediments, however, are a mixture of sand, silt, and clay in varying proportions. Therefore, in describing any particular sediment sample or any particular formation, it is necessary to have names which show the approximate relationship between the three size groups. Unfortunately, no nomenclature of this type has had any general acceptance in the past. On the other hand, it has been quite generally agreed that the triangle diagram with sand, silt, and clay in each corner presents the most graphic method of showing the relationships between the three grades. Accordingly, the attempt of the present paper will be to consider the various systems of subdividing the triangle that have been suggested in the past and to offer further suggestions with a hope of producing a standardization. That this hope may not be unjustified is indicated as a result of a questionnaire which was sent to a considerable number of sedimentationists. Good basic agreement was found among these scientists which gave hope that definitions could be made which would be widely used.

PREVIOUSLY SUGGESTED SYSTEMS

A considerable number of systems has been suggested for subdividing the sand-silt-clay triangle. Some of these systems are now used by engineers and soil scientists. Geologists have suggested other schemes but no wide use of them has been made so far as is known. Most of the systems are illustrated in figures 1 to 6.

The pattern illustrated in figure 1 was developed by the U. S. Army Engineers as a result of their extensive exploratory drilling program in unconsolidated sedi-

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[1] Contribution from the Scripps Institution of Oceanography, New Series No. 725. This investigation was supported by a grant from the American Petroleum Institute, Project 51.

[2] If it were not so difficult to extend analyses to the smaller grades, two microns would be a better dividing line between clay and silt since most clay minerals are believed to have diameters of less than two microns.

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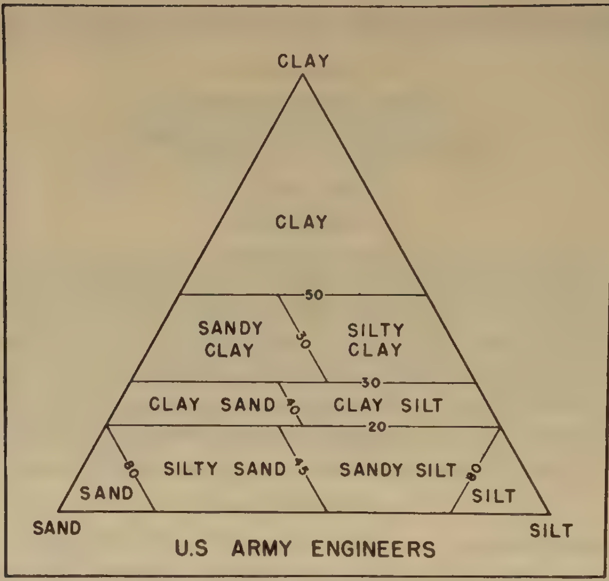

FIG. 1.—System used by U.S. Army Engineers. Per cent is indicated by the numbers which are written normal to each axis.

ments. It uses a simple nomenclature and boundaries which are parallel to one of the three sides of the triangle. It is based however, on laboratory tests of sediment samples which are not very significant to most geologists. The irregular sizes of the different subdivisions constitute a serious difficulty with using this system for marine sediment studies. Furthermore the boundaries are difficult to remember and there is no good central zone where the three sediment types are combined.

Figure 2 is a system used by soil scientists. It is simple and easily applied and might be quite useful to geologists for some purposes, particularly if "sand-silt-clay" was substituted for "loam" as indicated in the parentheses. The disadvantages of this system are (1) that it has too few groups to supply adequate nomenclature for sediment classification, and (2) that types near any of the three corners of the central triangle are poorly described by the names used. For example, it would be most unfortunate to call a sediment "sand" if it consisted of 51% sand and 49% clay.

A more complex system used by many soil scientists and engineers is indicated in figure 3. This system is more adequate than that of figure 2 and includes a central zone "clay loam," which would be useful, but it has other drawbacks. "Clay" covers an even larger portion of the diagram than in figure 1 and 2. It would seem unwise to use the word "clay" to describe a sediment with only 31% clay and higher per cents of either silt or sand. The very irregular subdivisions constitute a serious difficulty as in the case of figure 1. Perhaps the system is useful to soil scientists or engineers, but it is not applicable to descriptions of marine sediments.

Figure 4 shows a system which was suggested by Trefethen (1950). From the point of view of a geologist this system has obvious advantages over those shown in figures 1 to 3. The areas are nearly uniform in size and there is a general sym-

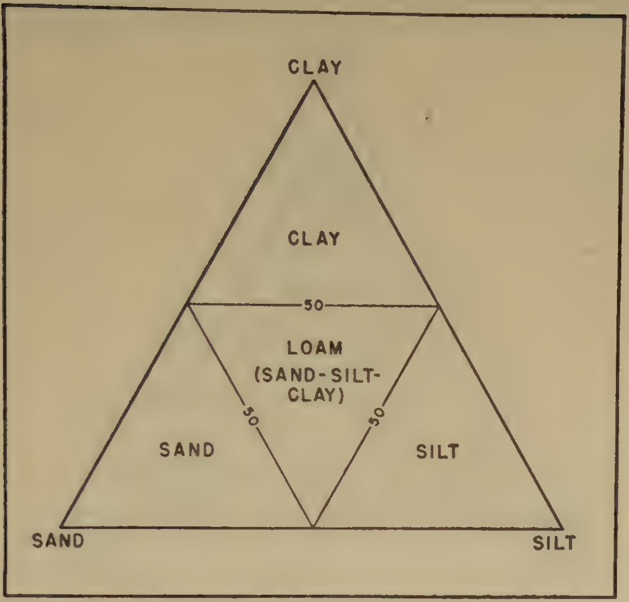
CLAY
CLAY
50
LOAM
(SAND-SILT-CLAY)
50
50
SAND
SILT
SAND
SILT

FIG. 2.—System proposed by Robinson (1949).

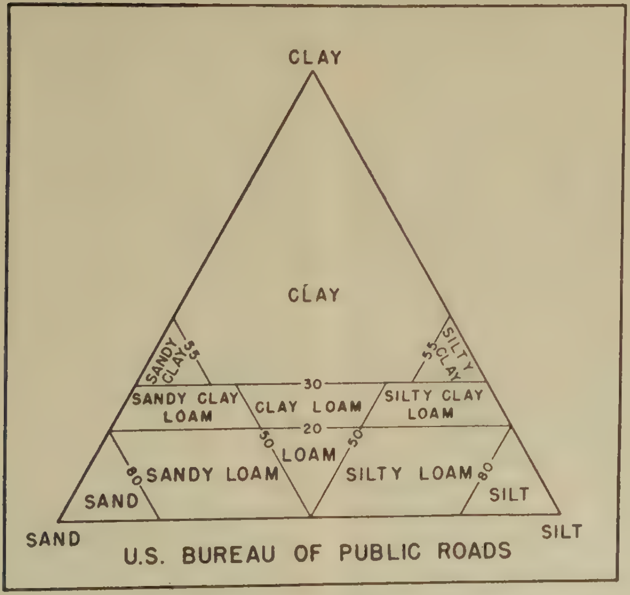
CLAY
CLAY
SANDY CLAY
55
55
SILTY CLAY
30
SANDY CLAY LOAM
CLAY LOAM
SILTY CLAY LOAM
20
50
50
LOAM
80
SANDY LOAM
SILTY LOAM
80
SAND
SILT
SAND
SILT
U.S. BUREAU OF PUBLIC ROADS

FIG. 3.—System used by U.S. Bureau of Public Roads.

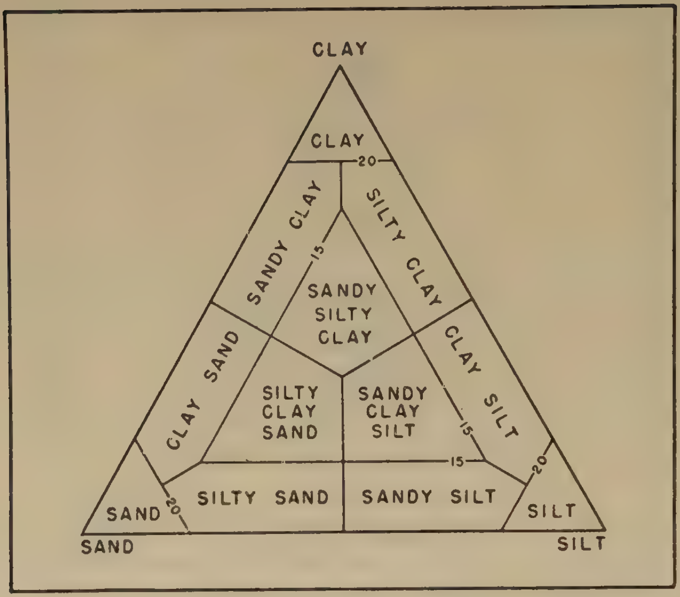

FIG. 4.—System proposed by Trefethen (1950).

metry so that the system is useful in describing the position of any particular sediment in the triangle. The names are all well-known although a minor inconsistency exists in the names "clay-silt" and "clay-sand" in contrast to "silty-clays," "silty-sands," etc. One more serious objection applies to the central zone. No name is given for a sediment which has approximately equal quantities of sand, silt, and clay. The analysis of sediments along the Gulf coast has indicated that this central area of the triangle may be very important. It would be awkward to use all three names to describe a general type of sediment, especially since each of the names consists of three words. Another minor, but important, objection lies in the rather large number of subdivisions which are difficult to remember.

Figure 5 represents a system developed in the early stages of A. P. I. Project 51 which was proposed largely to take care of field classifications but later on was applied to bottom sediment charts. It is based on the following principles: (1) to develop classes which could be distinguished without too much difficulty in the field, (2) to draw boundaries within the triangle between groups of previously analyzed sediments so as to separate natural subdivisions, and (3) to illustrate the general characteristics of size distribution with as few classes as possible. The uneven widths of the zones in the diagram are due in part to the easier recognition of some size contents than others. For example, 5% of clay in a clean sand is more obvious than 20% of clay in a silt. The large area indicated as "mud" was based on a test of field identification by a group of six geologists at Scripps Institution. It appeared that this large area could not be readily subdivided without laboratory analyses. Many difficulties developed in the use of the system, however, so that it has been abandoned. The supposed natural boundaries between sediment types became far less conspicuous after several thousand samples had been analyzed and plotted on the triangles. Also the irregu-

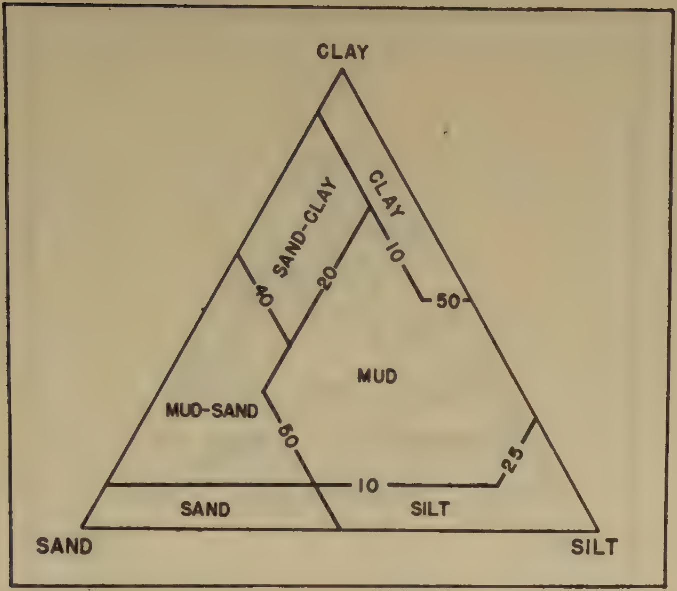

FIG. 5.—System first developed by API Project 51, later abandoned.

larity of the areas and lack of symmetry make the system difficult to remember. The use of the term "mud" caused serious objection partly because this term has been used very loosely by geologists and has grown to mean different things to different groups, particularly in the petroleum industry.

A more useful system, so far as natural subdivision is concerned, is illustrated in figure 6. This system which is a further breakdown of figure 5 was suggested by several members of A. P. I. Project 51. It has a much closer approximation to the natural boundaries between the large number of samples which have now been analyzed than is true of the system shown in figure 5. The ten percent lines are particularly useful in this connection, especially as regards such names as "sand," "silty clay," and "clayey silt." The wider subdivisions like "sandy mud" and "muddy sand" are also well justified, as is the large division called "mud." Some of the objections applied to the other systems, however, also apply to figure 6. It is difficult to find a good name to substitute for "mud." Also the large number of subdivisions and the lack of symmetry make the system complicated and difficult to remember.

SYSTEM PROPOSED FOR ADOPTION

The system indicated in figure 7 is not particularly different from some of the others, notably that of figure 4. The boundaries at the sides of the triangle are the same as those used by Krumbein and Sloss (1951, p. 122). It has some advantages over all of the other systems. There is one large central area, "sand-silt-clay," which can be used to describe the large group of sediments which consist of relatively uniform mixtures of the three grades of sediment. Except for a slightly larger central area, the rest of the subdivisions are rather uniform in size. The figure has symmetry and the boundaries are easy to remember. It was found that analyses from various sediment provinces, when grouped into the triangle, could be described quite adequately by

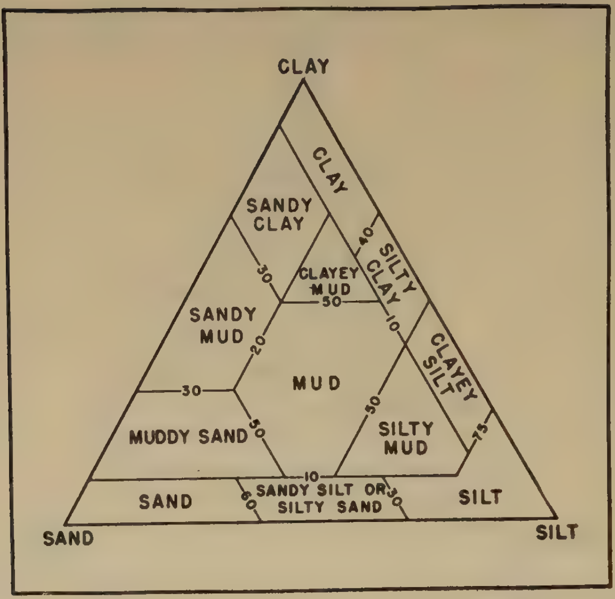

FIG. 6.—System proposed by some members of API Project 51.

these subdivisions (see for example fig. 8). It is only slightly less useful in this respect than figure 6, but certainly has the advantage over the latter in simplicity and symmetry, and in having more acceptable names.

The name for the central portion of figure 7 is unfortunate in one respect since it is difficult to have a threefold name of this sort. A possible substitute is the abbreviation "sansicl" which would be easy to remember (especially by the fathers of small children). This word was not used here partly because of objections to new nomenclature which is always difficult to establish. Some scientists would have preferred the word "mud" for this central zone. "Mud" certainly has the advantage of simplicity and it is unfortunate that it has grown into disrepute as a grade term.

The central zone of the triangle might be subdivided into the same groupings shown in figure 4, but this would again lead to the difficulties of an extremely complicated nomenclature for what is essentially a zone where the three sediment grades are each well represented.

RESULTS OF QUESTIONNAIRE

A questionnaire was sent to 40 sedimentationists and sediment laboratories and replies from 38 were received. In this questionnaire the diagrams (figs. 1 to 7 and a slightly modified form of fig. 7) were submitted and a preference was requested along with reasons for the preference. Most of the replies gave the order of preference of as many as three systems. Since it was felt that second and third choices should be given some consideration in a pool of results, it was decided to weigh the voting as follows: four points were given to a first choice, two to a second, and one to a third. Furthermore, in cases where it was stated that two systems were equally good, three points were given to each of these systems. Tabulating the votes by this method and combining the votes of the

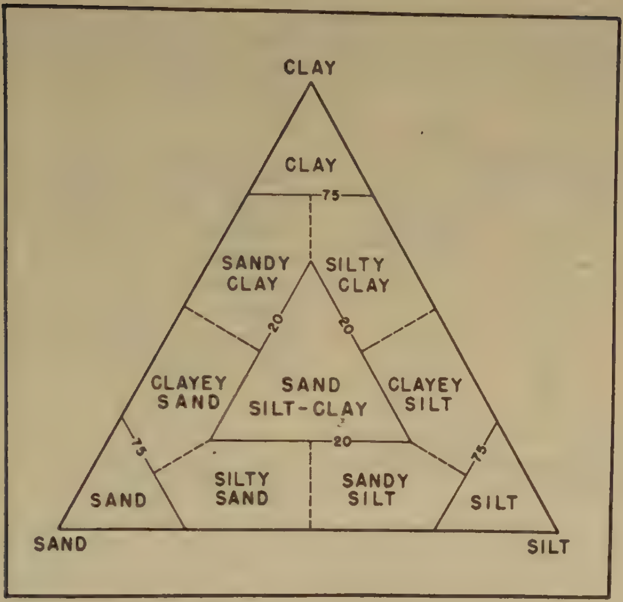
CLAY
CLAY
75
SANDY CLAY
SILTY CLAY
20
20
CLAYEY SAND
SAND SILT-CLAY
CLAYEY SILT
20
75
75
SAND
SILTY SAND
SANDY SILT
SILT
SAND
SILT

FIG. 7.—System which is recommended for general adoption, based on extensive discussion and correspondence with sedimentationists.

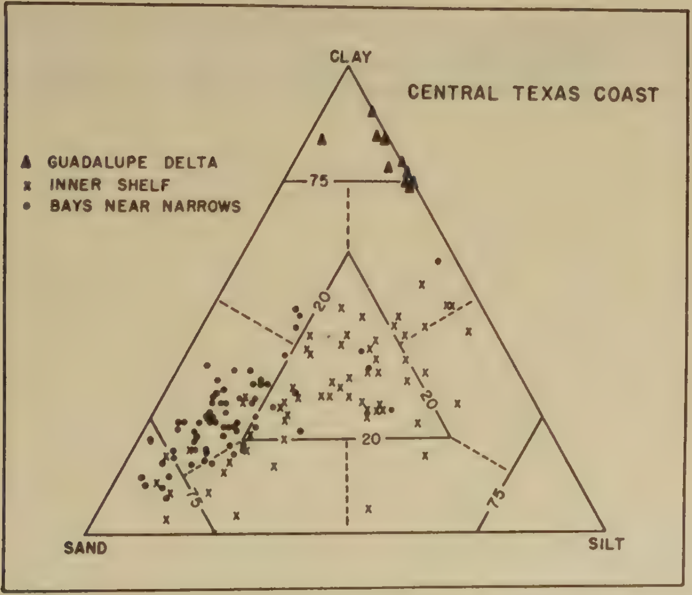

FIG. 8.—Application of system proposed in figure 7 to three sedimentary environments along the Texas coast. The "delta" samples represent a clay, the "inner shelf" samples a sand-silt-clay, and the "bays near narrows" samples a clayey sand.

system in figure 7 with those in a system that was almost identical, gave results (table 1) which indicate an overwhelming vote in favor of figure 7.[3] The same system was given the largest number of first choices. The system in figure 4 stood second in this respect and no other system received more than two first choice votes. It is significant that only one sedimentationist, who voted for more than one system, failed to include the system of figure 7 among the first three.

TABLE 1.—*Evaluation of systems by sedimentationists*

System	Points	No. given first choice*
Fig. 1	15	2
Fig. 2	4	
Fig. 3	6	1
Fig. 4	43	11
Fig. 5	18	1
Fig. 6	15	2
Fig. 7	139	16

* Does not include cases where two systems were considered equally good.

The results of the questionnaire answers seem to indicate that there would be few geologists who would object to adopting the system which is here proposed. It is hoped that this will be the case so that in the future it will become possible to describe sediments by these names and have the names denote the same meaning to all readers.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the help received from many students of sedimentation in developing the system which is proposed here. Special appreciation is due to the Steering Committee of A. P. I. Project 51 for their many suggestions, and to the Project staff, as well as the other geologists on the staff of Scripps Institution.

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[3] Including the nearly identical system.

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SEDIMENTARY ENVIRONMENTS DIFFERENTIATED BY COARSE-FRACTION STUDIES

BY

F. P. SHEPARD AND D. G. MOORE

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VOL. 38, NO. 8 (AUGUST, 1954), PP. 1792-1802, 4 FIGS.

SEDIMENTARY ENVIRONMENTS DIFFERENTIATED BY COARSE-FRACTION STUDIES[1]

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La Jolla, California

ABSTRACT

A simple non-technical system of characterizing sediments is described. In this the coarse fraction of each sample (the part greater than $\frac{1}{16}$ mm. in diameter) is sieved and the percentages of the significant constituents in each sieving are estimated from binocular examination of the subdivisions. The findings are compiled into diagrams and averaged for groups of similar sediments. The results appear to provide one of the best means of differentiating modern environments, and give important evidence of distances from shore, and water depths. It is thought that the method could be applied to help differentiate environments of ancient sediments.

INTRODUCTION

Recent sediments should provide the principal source of information for interpreting the environments of ancient sediments. It has, therefore, seemed unfortunate that most reports concerning recent sediments should continue to emphasize the traditional size-analysis factors with little or no discussion of other characteristics of the sediment which are commonly more important in diagnosing the sedimentary environments. In the American Petroleum Institute sedimentology project being conducted at Scripps Institution, various methods have been developed or amplified with the hope that more meaningful approaches can be made to sediment studies. One of the innovations is based on the binocular study of sieved coarse fractions from a number of sedimentary environments. This method has shown definite distinctions between a considerable number of environments and less distinct differences in others.

Coarse-fraction estimations can be made by any geologist who is familiar with the common constituents of sediments and the major groups of organisms. In fact, its possibilities were first indicated to the present writers because D. M. Poole in the course of sieving some of the coarse fractions noted the unusual color and texture of certain size fractions. Examination under the binoculars showed these consisted primarily of foraminifera. Inasmuch as the sediment was a silty clay with a very small coarse fraction, it seemed significant that the sieving had the appearance of a foraminiferal sand. Following this lead a great many samples were studied from the same general area along the Texas coast (in the vicinity of Rockport) and many examples were seen of the concentration of various constituents in particular sieve sizes. It was found also that the examination of individual sievings afforded a far better method of estimating percentages than was possible from the examination of the entire coarse fraction.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 726. This investigation was supported by a grant from the American Petroleum Institute Project 51, "Study of Nearshore Recent Sediments and Their Environments in the Northern Gulf of Mexico." Manuscript received, March 9, 1954.

[2] Scripps Institution of Oceanography, University of California. The writers appreciate the high quality of assistance received from Marjorie Browne, Bernadine Joyce, Harry Lusk, J. R. Moriarty, Elizabeth Sanborn, and Ruth Young. D. M. Poole, P. C. Scruton, and C. S. Wimberley contributed scientific data which formed an important contribution to the paper.

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The methods developed to show the results of these studies are preliminary and subject to improvement. Since many schemes were involved, it has seemed best to show most of them in the present paper along with examples to illustrate how each serves some purpose. It is to be hoped that others will suggest new methods. The coarse-fraction method of determining environments is not suggested as a replacement for conventional biological or petrographic procedures but as a tool to be used in conjunction with other techniques.

PREPARATION OF SAMPLES

Preparing samples for coarse-fraction study involves essentially the same technique as used in routine size analyses. Briefly, the procedure follows.

1. Dry and weigh the raw sample (approximately 30 grams, depending on sand content of sample).
2. Soak the sample in a solution of sodium hexametaphosphate in order to disaggregate flocculated clay particles and dissolve any minor amounts of salt which might tend to cement the grains.
3. Wash the sample through a 0.062 mm. (250-mesh) screen to separate the coarse and fine fractions. The fine fraction should be saved for determination of the percentages of silt and clay.
4. Dry the coarse fraction and, using a Rotap or similar device, sieve it to the standard Wentworth size grades.
5. Weigh each sieving and compute its weight percentage of the total sample.

BINOCULAR STUDIES

A cut from the various sievings is examined under the binocular microscope and estimates are made of the volume percentages of significant constituents.[3] It is preferable to have two people make independent estimates and compare results. In some cases it is possible to count grains but estimates of volume are still necessary because, despite the sieving, the grains will not be exactly the same size, and elongate material has a larger volume than the spherical grains and hence greater weight. Where two independent investigators develop percentages that are widely variant the sample is re-examined and an attempt is made to settle the difference. Where the percentage estimates are close, an average is taken of the two estimates. Where the sample is so large that it will cover more than the floor of the tray used for the examination it is advisable to use a micro-sample splitter. This will prevent overestimating of light flaky material which clusters on top.

The items to use in these estimates depend on the locality. In general, such materials as shells (which include fragments), Foraminifera, Ostracoda, echinoderm (principally echinoid) fragments, sponge spicules, plant fibers, glauconite, and various types of terrigenous minerals[4] are the most useful substances. The differentiation of the terrigenous minerals depends also on the locality. In areas where they consist predominantly of quartz and feldspar, it should not be necessary to differentiate. Elsewhere significant amounts of mica or other flaky minerals are found and should be given special treatment as they have an important relation to conditions of sedimentation. Similarly, if there are appreciable amounts of heavy dark minerals these also should be given a place in the classification. Grains imbedded in or coated with calcium carbonate or calcium sulphate may constitute important constituents in the diagnosis of the environment and should be included. No doubt many other constituents will be of value locally. If fecal pellets are considered of major significance, sodium hexametaphosphate can not be used as a dispersing agent.

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[3] Volume is preferable to weight since the latter is almost impossible to estimate. However, volume measurement for the total of the individual sievings is so difficult that it would be out of the question as a practical method. Probably the inconsistency of multiplying volume by weight produces errors which are smaller than those resulting from the estimations.

[4] Land-derived minerals such as quartz, feldspar, and ferromagnesians.

GRAPHIC PORTRAYAL OF RESULTS

There are several ways in which the results of estimating the percentages of constituents in the different size fractions can be portrayed in graphic form. To make the method most useful, it is desirable to show an average of a group of samples which appear to reflect the same environmental influences. The simplest way to show this average is indicated in Figure 1A. Here the percentage of constituents in each of the sieve sizes is given. This method alone does not give a complete picture, however, because it omits the weights of each size fraction. These weights can be shown as a histogram (Fig. 1B). To illustrate the total percentage of each constituent, pie diagrams as in Figure 1C are constructed. In both Figures 1B and 1C the estimates have been given as percentages of the coarse fraction and as percentages of the entire sample. If the total coarse fraction of a sample is small (say less than 1 per cent), it is necessary to show a pie diagram of the constituents of the coarse fraction alone, but the same type of diagram is helpful even if the coarse fraction is relatively large.

The variation between samples in the same environment is not indicated in these diagrams and may be very important because in some the spread may be so great that samples from one environment completely overlap those from another. In order to show this spread, a triangle diagram is used with the three most significant items given as the apices (Fig. 1D). This system was devised by Scruton (1953) to describe shelf sediments from the Aleutian Island shelf. It is possible to make two or more triangle diagrams for the purpose of comparing various elements in the coarse fractions. In order to compare percentages of major constituents with those of important minor constituents, it is necessary to multiply the minor percentages by some factor which will make them numerically comparable with the major constituents (Fig. 1D).

In most studies it is important to show how sediments vary with distance from source or away from the shoreline. For this purpose, profiles as in Figure 4 may be constructed with the percentages of constituents indicated for each station. Because some constituents will ordinarily possess a very high percentage and others a very low percentage, it is advisable to use probability graph paper with its expanded scale in the high and low percentages. Otherwise important variations may be difficult to see.

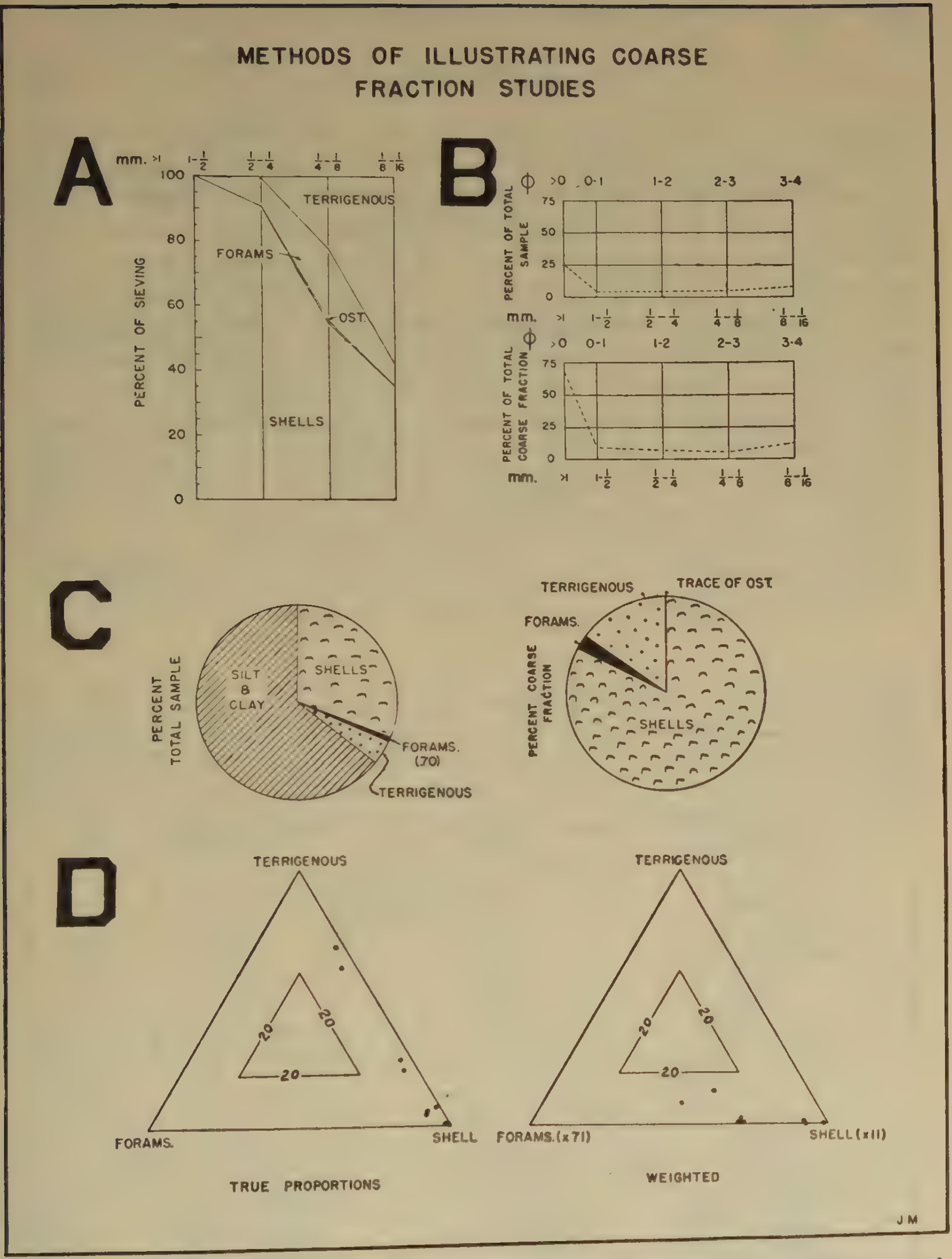


FIG. 1.—"Bays near oyster reefs," environment along central Texas coast, represented by several systems. "Terrigenous" refers to land-derived detrital minerals such as quartz and feldspar. A. Percentages of different constituents indicated for four sievings. B. Percentage of total sample and of coarse fraction included in five sievings. C. Pie diagrams. Left: percentage of silt and clay included. Right: coarse fraction constitutes entire pie. D. Triangle diagram: relation between foraminifera, terrigenous, and shell constituents. Right: foraminifera and shells have been multiplied by factor equal to average ratio of terrigenous sand to foraminifera and shells, respectively, for general area.

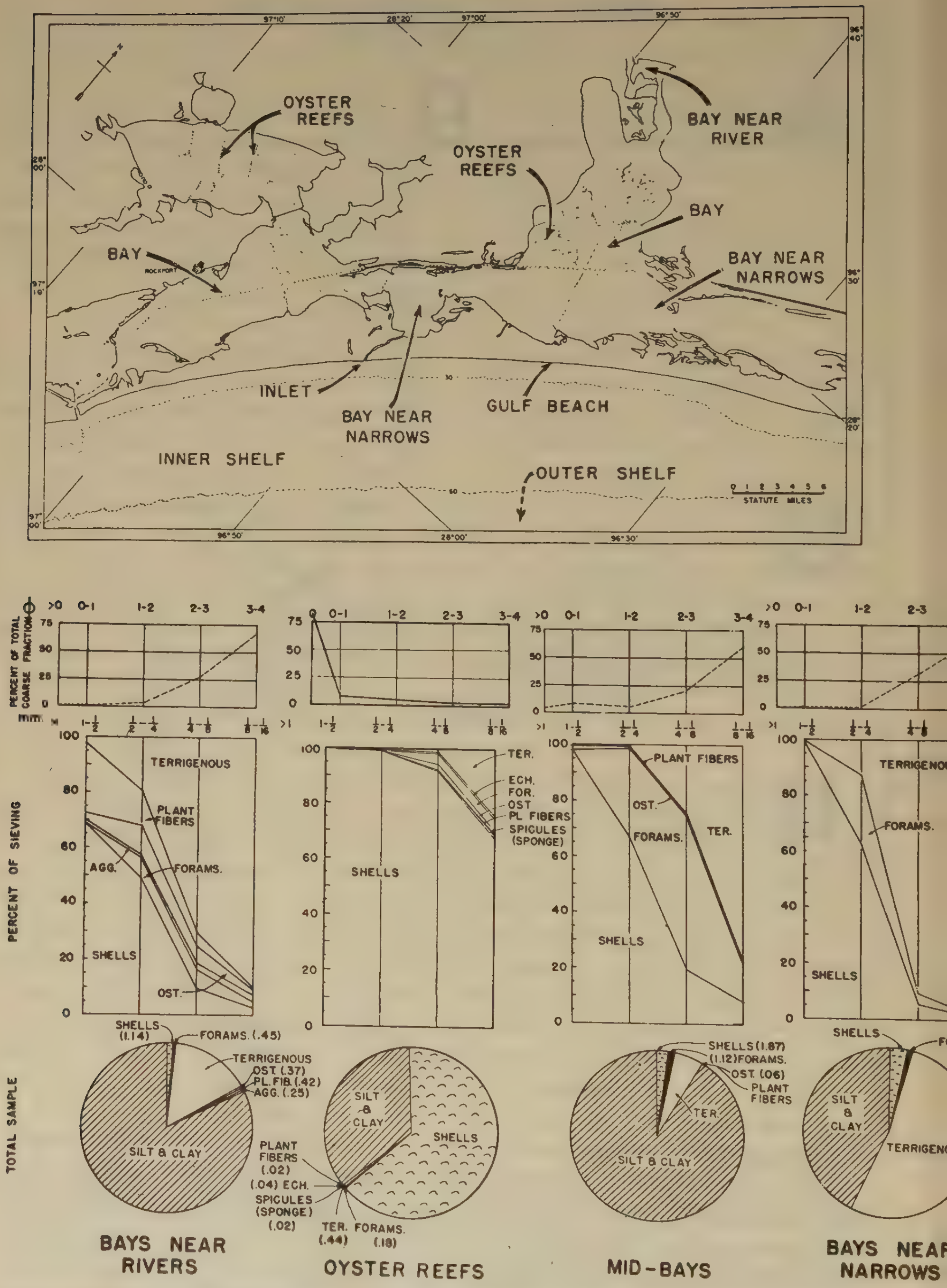
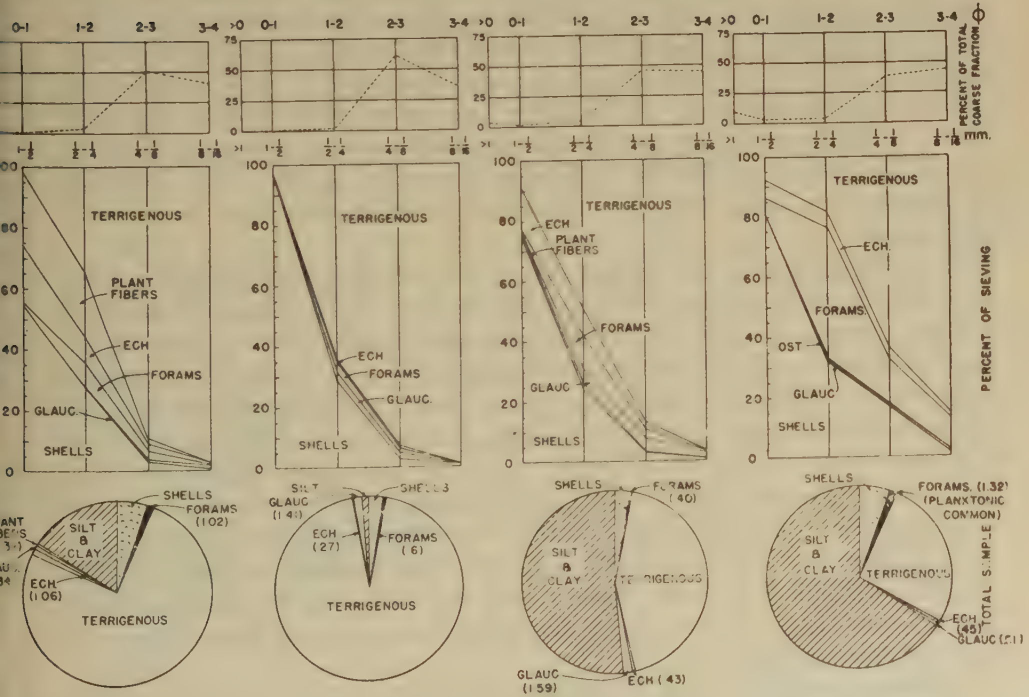


FIG. 2.—Environments in Rockport area along Texas coast as indicated by coarse-fraction studies. Typi

APPLICATION TO VARIOUS AREAS

Rockport, Texas, area.—Extensive sampling in the bays, on the barrier islands, and on the shelf in the vicinity of Rockport, Texas (30 miles northeast of Corpus Christi), provided an excellent opportunity to test the applicability of the coarse-fraction method. About 200 samples were studied in several different environments. These environments are related to the bays, the barrier islands, and the open continental shelf. Examples of the results are indicated in Figure 2. The parts of the "bays near rivers" are characterized by (1) a relatively high abundance of plant fibers which the river has carried into the bays, (2) the low percentage of coarse fraction resulting from the large amount of river-borne clay and silt, and (3) the preponderance of terrigenous minerals in the coarse fraction. Ostracoda are also very abundant in some samples. In the middle parts of the bays the coarse fraction is small but it has a large percentage of foraminifera and shells and a relatively small percentage of terrigenous minerals. The "bays near narrows," on the other hand, have a high percentage of terrigenous minerals and a large coarse fraction because the currents remove silt and clay and introduce



les of environments indicated by arrows on accompanying map. (For definition of "terrigenous" see Figure 1.)

sediment from the barrier islands where terrigenous sands constitute the bulk of the material.

"Inlets" within the barrier islands, because of lateral migration, constitute an important depositional environment. The sediments from this environment have a large coarse fraction and contain an abundance of shells. Unlike the bays, the inlet sediments include significant amounts of echinoids and glauconite.[5] The beach sands are remarkably free from shells and foraminifera because of the grinding effect of the waves, so that terrigenous minerals of sand-size constitute the bulk of the sample. A small amount of echinoids and glauconite is found in most of the open Gulf beaches, whereas these materials are absent in most bay beaches.

The "inner shelf" environment, with depths of about 5–20 fathoms, is characterized by a coarse fraction of 25–50 per cent, which is larger than in most bay sediments. Shells and foraminifera are represented although not to such a degree as in some of the bay environments. Glauconite and echinoid fragments are present in greater amounts than is characteristic of the barrier island sediments. The "outer shelf" shows an increase in shells and foraminifera, whereas there is a decrease in glauconite. In some samples foraminifera constitute a greater percentage of the coarse fraction than do the terrigenous minerals. Foraminifera include abundant pelagic types, especially the easily recognized Globigerinidae. These pelagic types appear to assume importance at about 20 fathoms which is used here as the dividing line between the inner and outer shelf. A considerable variation in the total percentage of the coarse fraction is found on the outer shelf. In one line of samples southeast of the Rockport area the coarse fraction constitutes less than 1 per cent but in another it runs as high as 20 or 30 per cent. In both areas, however, the other characteristics are those of the "outer shelf" environment.

The effectiveness of the coarse-fraction method for differentiating environments in this area has become evident from two tests. In one, diagrams like those in Figure 1 were examined for a series of 50 studied samples without knowing the locality. It was found possible to place almost all of these samples in the correct environment. In the other test, 10 previously unstudied samples were used and the environment of each was assigned without knowing the locations. Only one of these samples proved to be of doubtful nature. The same test was given to specialists in the field of Foraminifera, Ostracoda, and to those who had been studying the special relationships of grain size. The coarse-fraction studies indicated environments more accurately than the other methods although the foraminifera were almost as useful. These results may have been fortuitous and tests in other areas should be made before giving too much emphasis to the importance of coarse-fraction studies.

Sediment changes out from Mississippi Delta.—P. C. Scruton has applied the

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[5] An authigenic mineral of special significance because of its marine origin.

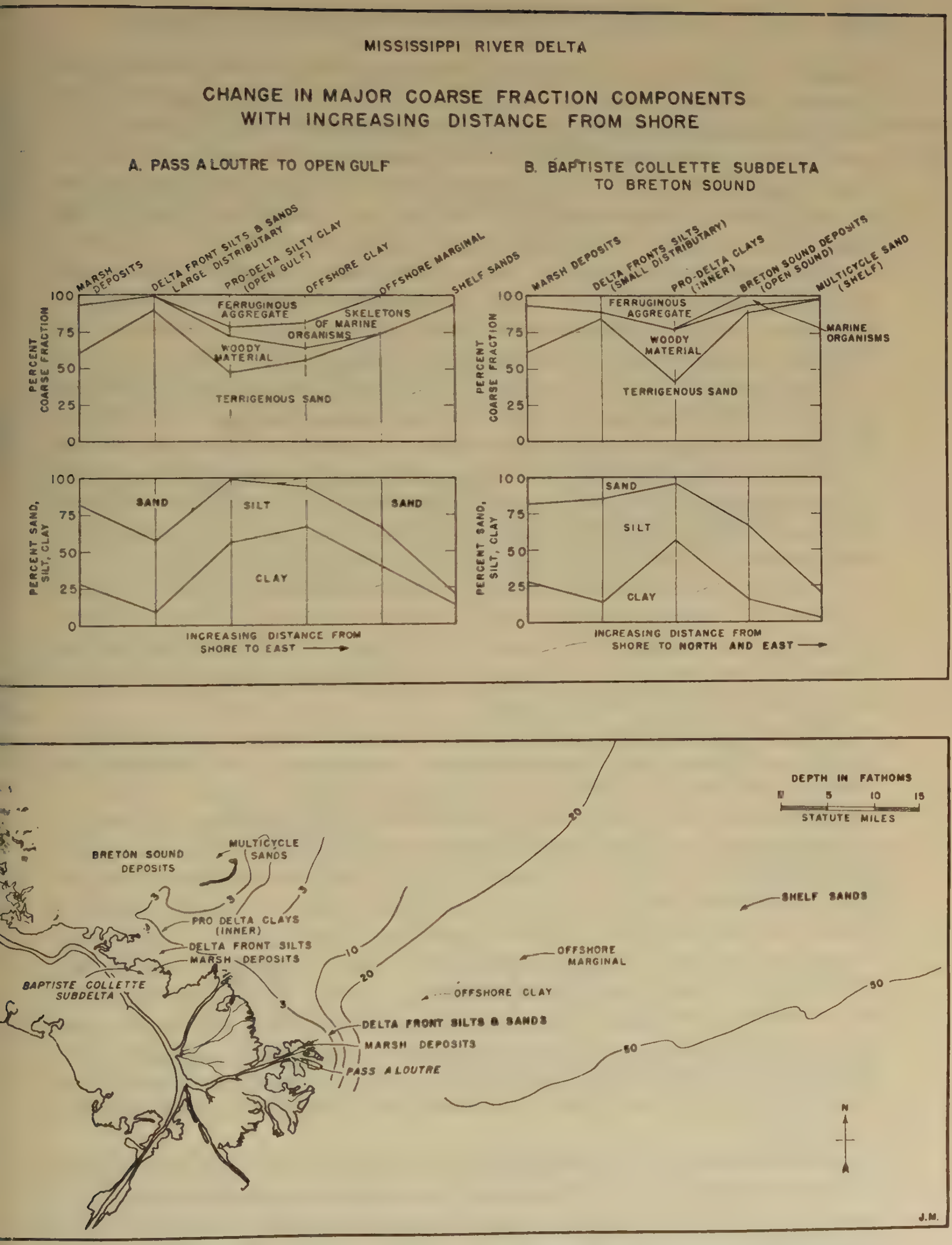

FIG. 3.—Variation in coarse fraction related to distance from distributaries of Mississippi Delta. Averages for each environment given in graphs and approximate locations of environment shown by arrows. (Data supplied by P. C. Scruton.) (For definition of "terrigenous" see Figure 1.)

coarse-fraction method to the study of the large suite of samples obtained by American Petroleum Institute Project 51 off the east side of the Mississippi Delta. A somewhat different grouping of diagnostic constituents is found in this area, including terrigenous sands, woody materials, skeletons of marine organisms, and ferruginous aggregates. Figure 3 shows sections extending east from Pass a Loutre to the open Gulf and north and east from Baptiste Collette Subdelta to Breton Sound. The coarse fraction in both sections shows a decrease in woody materials in the delta front deposits where there has been dilution by rapid terrigenous sand deposition, a relative increase farther from the distributaries, and then a drop to negligible amounts at significant distances from the delta. The ferruginous aggregates follow the same sequence as the woody materials but their characteristics indicate they may have formed in the sediment after deposition. The marine organisms, on the other hand, increase continuously away from the delta until reworked shelf sand deposits are encountered where they decrease.

In places the sand-silt-clay contents are controlled by a dual source. The sand of the outermost zone in each sequence is not being introduced by the present Mississippi River system. The fine sediment from the river is either bypassing these areas or is not carried that far east to any appreciable extent.

It will not be surprising if sections prepared from other deltas show similar progressions. In many other localities the muddy sediments off large river deltas are flanked by off-lying sands (Shepard *et al.*, 1949, and Shepard, 1948, pp. 114, 123–29). There are reasons to believe that these also are residual or related to sources other than the present rivers.

Sediment sequence across a narrow southern California shelf.—A series of samples from southern California collected and studied by C. S. Wimberley and Shepard indicates an application of the coarse-fraction method to open-shelf sediments in an area where the shelf is narrow and sediment supply is relatively low because of the small rainfall. Material washed from the cliffs and the small canyons which cut the cliffs is probably a more important source of sediment than is the outflow from Sorrento Valley which occurs only during exceptional floods. The section extends from the beach out to the upper part of the continental slope. In this area (Fig. 4) it has been proved important to use different subdivisions of the coarse-fraction components than in either of the Gulf Coast areas. The terrigenous sand was estimated as light minerals (principally quartz and feldspar), dark minerals (other than biotite), and mica. The organisms were divided into shells, foraminifera, and echinoids. Plant fibers also were included in the estimates. A probability type graph was used to exaggerate the small percentages.

The coarse-fraction constituents have an interesting progression seaward. The change directly outside the beach is especially pronounced. The quantity of mica is more than doubled, and echinoids and foraminifera first appear, whereas percentages of dark minerals and shells decrease. In general, the beach showed a simpler composition, consisting largely of light terrigenous minerals. Sample 8

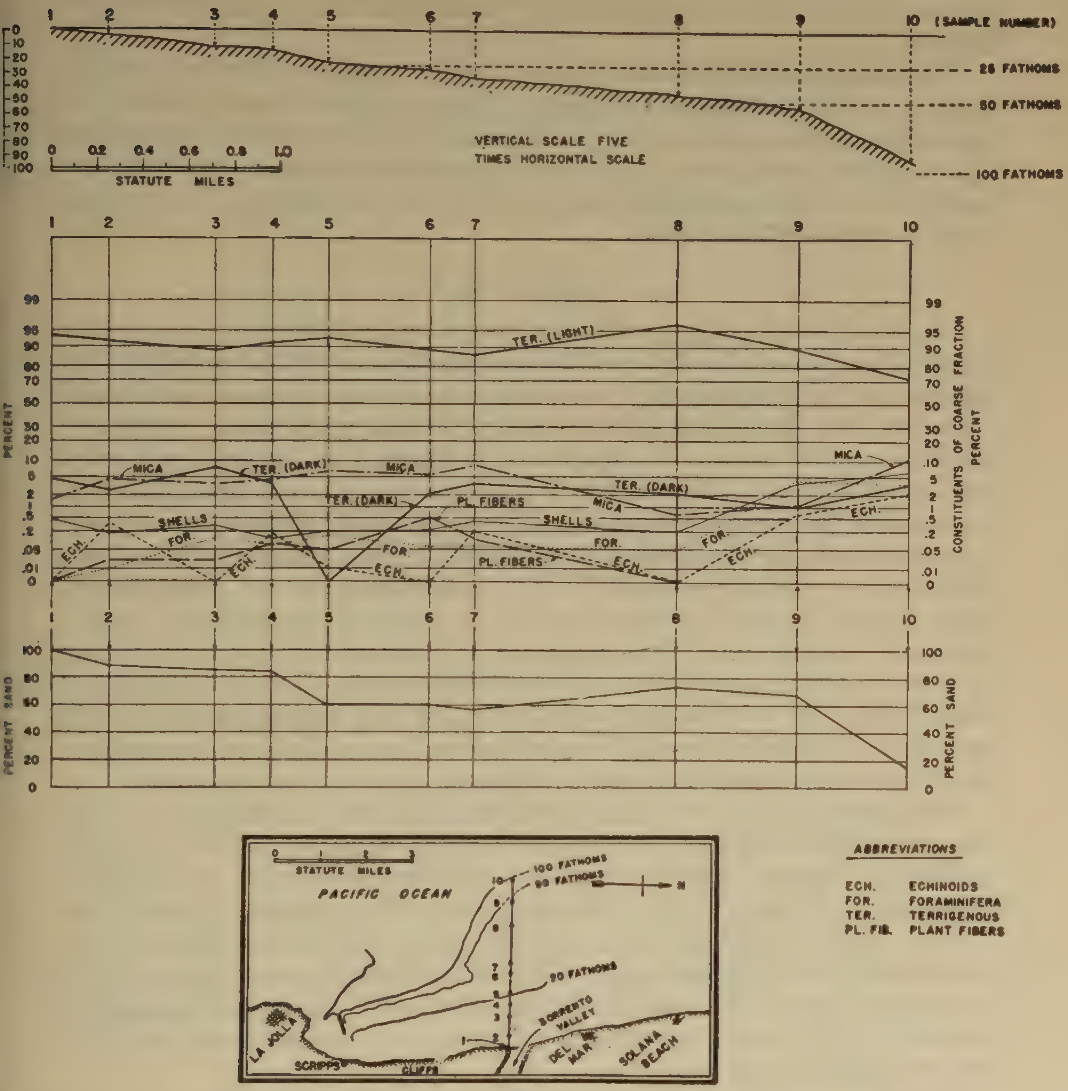

FIG. 4.—Variation in coarse-fraction constituents related to distance from shore in southern California area. Note relation of submarine topography shown in profile to sediment constituents and percentage of sand. (For definition of "terrigenous" see Figure 1.)

near the break in slope is more like the beach than the other intermediate samples. An impressive feature of change in the coarse fraction in the seaward direction is the marked increase in all of the organism groups and of mica in the two outer samples. The coarse fraction constituents and the sand percentages both suggest that the outer-shelf sediment has a source other than that which is now supplying the inner shelf. Also a strengthening of currents on the outer shelf may be indicated.

The sand percentage shows a decrease seaward except in the case of samples 8 and 9 near the shelf edge where there is a distinct increase in sand content and also an increase (not shown here) in the coarser grades of sand so that there is more sediment coarser than 0.25 millimeter than is found even on the beach. It is notable that the decrease in sand content on the inner shelf shows a curve similar to the profile of the sea bottom.

CONCLUSIONS

The illustrations included in Figures 2 to 4 afford evidence that the binocular examination of coarse-fraction sievings can provide a useful tool to indicate the direction of the shoreline and of the source of sediment. It seems particularly important that the method can be used in such diverse regions. However, it should be appreciated that the significant constituents of the sediment are not the same in different regions so that it is necessary to make a careful choice of the materials for the analysis in each area. It is also clear that the best results will come only from the coordination of information from coarse-fraction analysis with all other available methods. In the three illustrations the importance of grade sizes in making the determinations is indicated. Foraminifera, macro-organisms, and Ostracoda are all recognized as important guides to environment but, like the coarse-fraction method, when taken individually may be deceptive. There has been too much interpretation in the past from single methods. It would seem that the specialists should broaden their outlook and give more consideration to the general composition of the sediments which they are examining.

In a general application of the coarse-fraction method to the study of sedimentary rocks, disaggregation will undoubtedly be the major problem. A limited application can come from the dissolving of sandstone cement, but important constituents are likely to be lost by such a process. The estimation of percentages could be made by studying polished sections where the coarse fraction is relatively large although the advantage of the sieving of different size fractions would of course be lost by this method. On the other hand, many semi-consolidated materials will no doubt be fit subjects to the complete coarse-fraction method if they are disaggregated with care.

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(*Reprinted from Nature, Vol.* 174, *p.* 469, *September* 4, 1954)

A Deep Sounding from the Southern Hemisphere*

It is well known that the great trenches of the Western Pacific represent larger vertical departures from the level surface of the geoid than even the Himalayas. But our knowledge of the shape of the ocean floor is still so fragmentary that the question as to which trench is the deepest has received several different answers within the past two decades. The Mindanao Trench east of the Philippines was long believed to contain the greatest oceanic depth; but for a few years prior to 1950 many authorities considered that the U.S.S. *Ramapo* soundings in the Japan Trench were the deepest yet recorded. In that year Hess and Buell[1] re-examined the data and concluded that the sounding of 5,740 ± 50 fathoms obtained in the Mindanao Trench by the U.S.S. *Cape Johnson* during the Second World War represented the greatest depth. H.M.S. *Challenger* in 1951 made still deeper soundings in the Marianas Trench east of Guam. These were reported by Carruthers and Lawford[2], and later Gaskell, Swallow and Ritchie[3] stated that the maximum depth lay between 5,882 and 5,940 fathoms.

In December–January 1952–53, during the Capricorn Expedition of the Scripps Institution of Oceanography, the research vessels *Horizon* and *Spencer F. Baird* made twenty-four echo-sounding lines across the Tonga Trench between lat. 14° 30′ S. and 26° 15′ S. *Horizon* found the area of greatest depth more than 5,500 fathoms near the abrupt change in trend of the trench axis 180 miles south of the island of Tonga Tabu. In this "Horizon Deep"[4], soundings were taken by recording the echoes from explosions in order to eliminate some of the sources of absolute error inherent in the echo-sounding apparatus. Positions were determined by dead reckoning between morning and evening star sights supplemented by meridian altitudes of the sun at noon.

As the ship proceeded at about 7·5 knots, half-pound demolition blocks with 14-in. fuses were dropped overboard at 3–10 min. intervals. The charges exploded 10–13 fathoms below the surface; the firing mark and echo-train were received on the echo-sounder hydrophone and were recorded by a pen oscillograph. Timing marks were placed on the record at 1-sec. intervals using a break-circuit chronograph. The longest time of travel for the first

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* Contribution from the Scripps Institution of Oceanography, New Series, No. 727.

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echo was measured at lat. 23° 15·5′ S. and long. 174° 36·5′ W.

Assuming that this echo came from directly beneath the ship, and using velocities of sound at different depths computed with the aid of Kuwahara's tables[5] from temperature and salinity measurements by *Spencer F. Baird*, 200 miles north of *Horizon's* position, the time of travel corresponds to a depth of 5,814 fathoms (10,633 m.). If this were accepted as the true value, it would be the deepest sounding yet recorded from the southern hemisphere; it would exceed the Galathea Depth in the Mindanao Trench[6] by 50 fathoms and would be second only to the soundings obtained by H.M.S. *Challenger* in the Marianas Trench.

An investigation of the uncertainties involved in the depth of explosion of the charges, in reading and correcting the records, in the timing circuit of the oscillograph, and in the computed velocities of sound, indicates that the combined error from these causes is less than ± 15 fathoms. The consistency of the travel times recorded from successive explosions shows that true sea-floor echoes were obtained. But careful comparisons of the first and subsequent echoes from each shot on the line of soundings show that the first echo at the above stated position came from the relatively gentle eastern slope of the trench, and that the actual depth directly under the ship was somewhat greater. Because of the V-shaped cross-section of the trench, a 'masked' zone extended for a distance of two miles west of the position. Here the first echoes to arrive came from the steeply sloping west wall rather than from the bottom beneath. Graphical analysis of the travel times of the second echoes indicates that the deepest point actually lies near the centre of this masked zone at about 5,900 fathoms but with a rather large uncertainty. Thus the Tonga Trench may be deeper than even the Marianas Trench; measurements with a narrow beam echo-sounder are needed to resolve the question. A detailed discussion will be published shortly by one of us in the *Journal of Deep Sea Research.*

It is remarkable that all three of the greatest measured ocean depths, though recorded from widely separated areas, lie within 200 fathoms of each other in the V-shaped portions of deep trenches. This close agreement may reflect both the nature of the trench-producing forces and the strength of the earth's crust.

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GYMNODINIUM SPLENDENS, A MARINE DINOFLAGELLATE REQUIRING VITAMIN B_{12}

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GYMNODINIUM SPLENDENS, A MARINE DINOFLAGELLATE REQUIRING VITAMIN B_{12} [1,2]

Beatrice M. Sweeney

GYMNODINIUM SPLENDENS is a marine dinoflagellate which can be cultured successfully in mineral-enriched sea water in the presence of soil extract. Soil extract contributes some factor, necessary for the continued growth of this organism, which cannot be replaced by the better-known vitamins or amino acids, or by yeast extract (Sweeney, 1951). Robbins et al. (1950) have shown that water extract of soil is a rich source of the cobalt-containing vitamin B_{12}. Yeast extract is known to be a poor source of this vitamin (Peeler et al., 1951). In 1949, Hutner et al. reported that vitamin B_{12} is required for the growth of the green flagellate, *Euglena gracilis*. Since that time, a number of other organisms have been found to require an external source of this vitamin, including the marine diaton, *Amphora perpusilla*, and the brackish water dinoflagellate, *Gyrodinium* sp. (Provasoli and Pintner, 1953). These observations suggested that vitamin B_{12} might be the factor in soil extract which is required for the growth of *Gymnodinium*. The following paper reports the results of experiments to test this possibility.

BACTERIA-FREE CULTURES.—Because bacteria are known both to consume and to produce vitamin B_{12} (Darken, 1953), it was important to obtain bacteria-free cultures of *Gymnodinium splendens* for the purpose of this study. Mixtures of penicillin and streptomycin have been employed to obtain sterile cultures of the marine diatom, *Nitzschia closterium*, by Spencer (1952).

Provasoli et al. (1951) report success in freeing a number of algae and protozoa from bacteria with mixtures of antibiotics. Oppenheimer (1954) was able to reduce the number of viable bacteria in sea water with various antibiotic mixtures, the most successful of which was penicillin-streptomycin-chloromycetin, each at a concentration of 50 p.p.m. In preliminary attempts to obtain pure cultures of *Gymnodinium*, cells were treated with mixtures of these three antibiotics at the same concentration. Since chloromycetin proved to be toxic, while penicillin and streptomycin did not inhibit the growth of *Gymnodinium*, a mixture of penicillin and streptomycin was selected for further trial. A small number of cells were exposed to this antibiotic mixture in culture medium for 24 hr. By such treatment, a clone of *Gymnodinium* was obtained which, after many transfers, remained free of bacteria or other contaminating organisms. The absence of bacteria was established by plating on sea water agar plates (1.5 per cent agar) supplemented with mineral nutrients, 0.05 per cent peptone, and 0.001 M acetate. The pure culture obtained was employed in the study reported below.

METHOD.—The strain of *Gymnodinium* used in this study was originally isolated from a net sample on January 11, 1952. Cultures were grown in cotton-plugged pyrex test tubes. All glassware was washed in soap, and boiled in dilute nitric acid, then in distilled water. Sterile technique was followed.

The mineral nutrient culture medium was essentially that used previously for *Gymnodinium* (Sweeney, 1951). Aged sea water (collected Oct. 18, 1951) was diluted to 75 per cent of full strength with twice-distilled water and supplemented with KNO_3 2×10^{-3}M, K_2HPO_4 2×10^{-4}M, $FeCl_3$ 6×10^{-6} and $MnCl_2$ 6×10^{-7}M. Since soil extract contains chelating agents capable of binding heavy metal ions (Hagens, 1953), the chelating agent, disodium ethylene diamine tetra-acetate (EDTA) was included in the medium (10 mg. per l.). This substance is not known to have any effect on cell metabolism. It serves to form complexes with heavy metal ions in the medium, thus reducing the concentration of free metal ions, while prolonging their availability (Hutner et al., 1950).

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The author wishes to express her gratitude to Dr. Karl Folkers for very kindly supplying crystalline vitamin B_{12}; to Dr. Carl Oppenheimer for the antibiotics penicillin G, dihydro-streptomycin sulfate and chloromycetin; to Dr. Marion Cramer for Hutner's strain of *Euglena gracilis* var. *bacillaris*; and to Dr. Francis Haxo for suggestions made during the preparation of this manuscript.

[2] Contribution from the Scripps Institution of Oceanography, University of California New Series No. 728.

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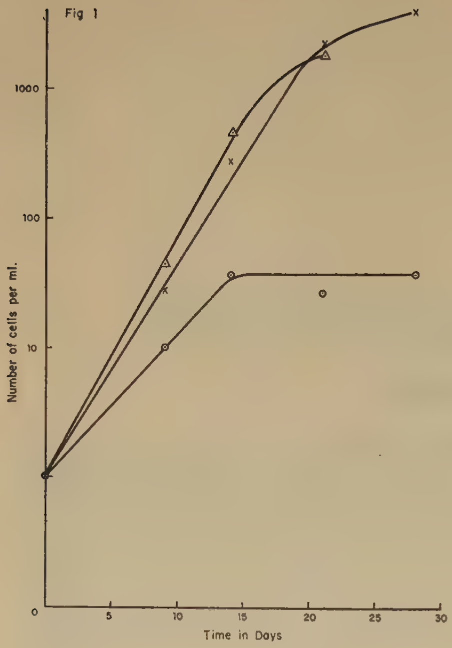
Fig 1

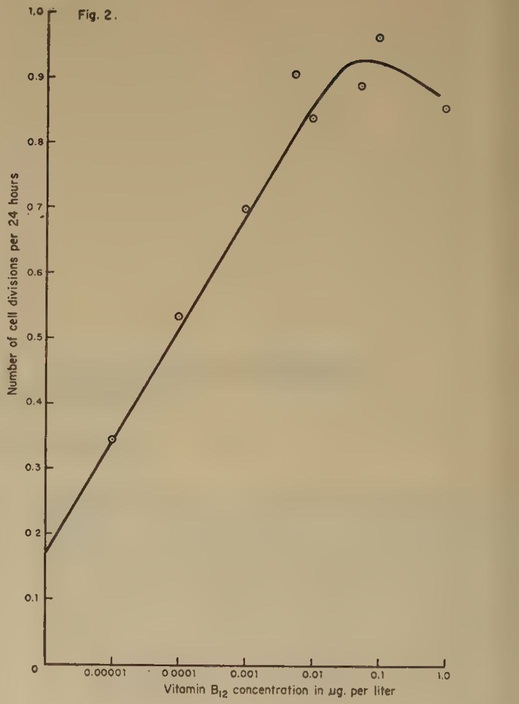
Fig. 2.

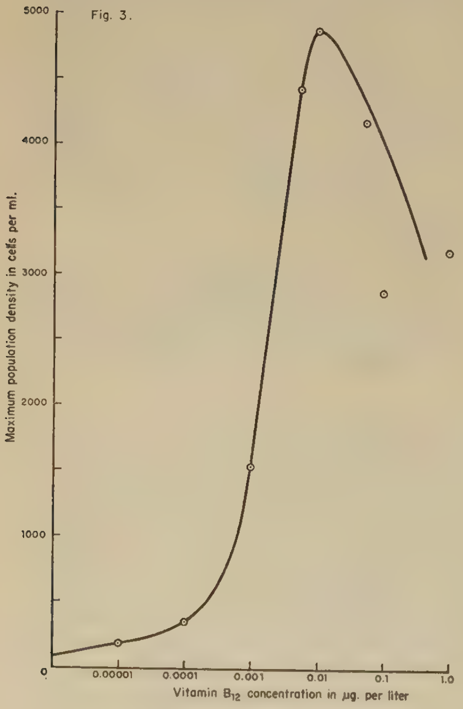
Fig. 3.

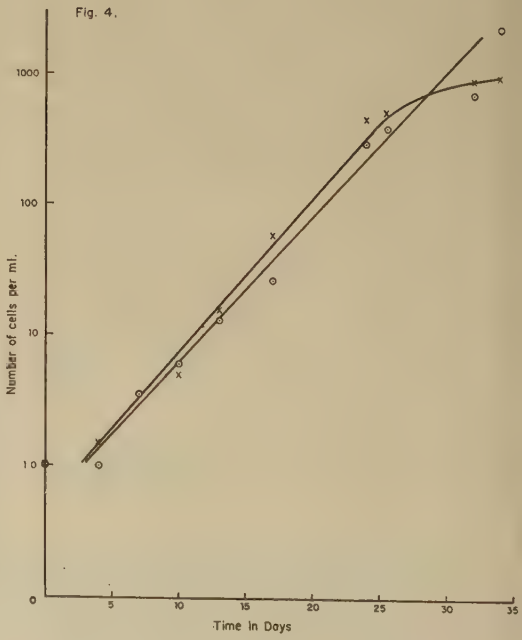
Fig. 4.

A stock solution of crystalline vitamin B_{12} (cyano-cobalamin) was made up in sterile twice-distilled water, and sterilized by boiling for one minute. Vitamin B_{12} was added to the medium after autoclaving.

Most cultures were grown at room temperature, illuminated by daylight from a window with a northern exposure, where the approximate range of light intensity was 200–400 ft.–c. during the day. In later experiments, some cultures were grown in an illuminated refrigerator at 20 ± 1°C. and constant fluorescent light of 300–400 ft.–c intensity.

Bioassay for vitamin B_{12}.—The vitamin B_{12} content of soil extract was determined by bioassay with *Euglena gracilis* var. *bacillaris.* The bioassay method was essentially that of Robbins et al. (1950), but the liquid medium used was that of Cramer and Myers (1952). The absorption of the cell suspension was measured with a Beckman spectrophotometer at 675 mμ. Maximum growth of *Euglena* was reached at 0.1 μg. vitamin B_{12} per l., a value in agreement with that of Hutner et al. (1949) and Robbins et al. (1950).

EXPERIMENTAL RESULTS.—When vitamin B_{12} (0.1 μg. per l.) was substituted for soil extract in mineral-enriched sea water containing EDTA, *Gymnodinium* grew during many transfers at the same rate, and reached the same maximum population as when soil extract was present (fig. 1). For determinations of the quantitative requirements of *Gymnodinium* for vitamin B_{12}, cells were used as inoculum which had been depleted of stored vitamin by passage through several subcultures in medium deficient in vitamin B_{12}. The growth rates and maximum populations at different vitamin B_{12} concentrations, obtained with depleted cultures, are shown in fig. 2 and 3. Maximum growth was obtained at 0.01 μg. vitamin B_{12} per l. Thus, *Gymnodinium* reaches peak growth at somewhat lower vitamin B_{12} concentrations than does *Euglena gracilis.* At vitamin B_{12} concentrations higher than 0.01 μg. per l., the logarithmic phase of growth was of shorter duration, and a lower maximum population density was attained.

The vitamin B_{12} content of a sample of soil extract which had been shown to possess growth-promoting activity for *Gymnodinium* was determined by bioassay, as described above. This soil extract was found to contain the equivalent of 1.6–1.8 μg. vitamin B_{12} per l. or 0.0016–0.0018 μg. per g. fresh weight soil (approximately 0.002 μg. per g. oven-dry soil). Culture media which contained 4 per cent soil extract therefore had a vitamin B_{12} activity of about 0.06 μg. per l., or sufficient vitamin B_{12} to bring about maximum growth of *Gymnodinium.*

A number of bioassays of the same soil extract have been carried out at different times after its preparation. No consistent change in the vitamin B_{12} activity of any soil extract with age could be detected. Changes in some other component must account for the ageing effect of soil extract previously described (Sweeney, 1951).

The effect of EDTA.—Although the inclusion of EDTA in culture media gave more reproducible growth rates, the presence of EDTA is not essential for the effective replacement of soil extract by vitamin B_{12}. *Gymnodinium* has been subcultured for over ten months in medium containing vitamin B_{12} in the absence of EDTA.

When cells are transferred from complete medium into medium without vitamin B_{12}, *Gymnodinium* continues to grow for some time at the expense of vitamin stored within the cells. When EDTA is present in this vitamin-deficient medium, the time of survival of the culture is prolonged somewhat, as compared with that of cultures in mineral-enriched sea water alone. However, *Gymnodinium* cannot be maintained indefinitely in mineral-enriched sea water containing EDTA. Bioassay of EDTA solutions for vitamin B_{12} gave negative results.

There was no evidence of micronutrient deficiency in media containing vitamin B_{12} and EDTA, 10 mg. per l. The growth of *Gymnodinium* was the same in this medium with or without the micronutrient solutions A_4 and B_7 (Arnon, 1938), as shown in fig. 4.

The aged sea water employed in the culture medium for *Gymnodinium* showed no detectible vitamin B_{12} after autoclaving, at concentrations of 1, 5, and 10 per cent. The increase in salinity caused by the addition of 10 per cent sea water to the bioassay medium had no appreciable effect on *Euglena.*

On the basis of its nutrition, then, *Gymnodinium splendens* may be classified as an auxotroph: it is able to carry on photosynthesis, but its synthetic capacity is impaired to the extent of requiring an external source of vitamin B_{12}.

Fig. 1–4.—Fig. 1. Growth of *Gymnodinium* in media supplemented with soil extract or with vitamin B_{12}. o–o o: mineral-enriched sea water with micronutrients and EDTA, 10 mg. per l. x-x-x: same medium containing 4 per cent soil extract. Δ-Δ-Δ: same medium containing vitamin B_{12}, 0.1 μg. per l. Each point represents the average of three determinations.—Fig. 2. Rate of cell division of *Gymnodinium* in different concentrations of vitamin B_{12}. Cultures grown at 20°C. with constant light of 400 ft.–c. intensity. Inoculated from cultures depleted of vitamin B_{12} by three passages through medium containing 0.0001μg. vitamin B_{12} per l., and one passage in 0.0001μg. vitamin B_{12} per l. Each point represents the average of three determinations.—Fig. 3. Maximum cell populations of *Gymnodinium* in different concentrations of vitamin B_{12}. Cultural conditions the same as in fig. 2. Each point represents the average of three determinations.—Fig. 4. Growth of *Gymnodinium* with and without supplementary micronutrients. o-o-o: mineral-enriched sea water containing EDTA, 10 mg. per l. and vitamin B_{12}, 0.1μg. per l. x-x-x: same medium containing micronutrients of Hoagland and Arnon's A_4 and B_7 solutions. Each point represents the average of four determinations.

SUMMARY

Gymnodinium splendens, a marine dinoflagellate, has been obtained in bacteria-free culture by the use of a mixture of penicillin and streptomycin. This dinoflagellate cannot be cultured in sea water enriched with mineral nutrients alone, but requires a growth-promoting factor present in soil extract. The factor from soil extract has been shown to be replaceable by vitamin B_{12}. *Gymnodinium* may be subcultured indefinitely in mineral-enriched sea water containing vitamin B_{12}. The optimum vitamin B_{12} concentration for growth lies between 0.01 and 0.1 μg. per l. Bioassay with *Euglena gracilis* confirmed the presence of sufficient vitamin B_{12} in soil extract to account for its growth-promoting activity for *Gymnodinium*.

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FOREWORD

By Roger Revelle

Of all earth's phenomena, coral reefs seem best calculated to excite a sense of wonder. And of all the forms of coral reefs, the atolls have appeared to men of science to be richest in mystery and most strange. Rising alone from the empty sea, these ancient structures, growing now slowly, now fast, toppling when the sea retreats and flung up in haste when sea level rises, are like a Gothic cathedral, ever building yet never finished, infinite in detail yet simple and massive in plan. Tiny plants and animals are their builders. Their architects are the giant ocean and the restless wind.

Reef corals and calcareous algae can grow only within a few hundred feet of the sea surface, yet most atolls rise as isolated structures many thousands of feet above the ocean floor. Is the coral and other calcareous skeletal material simply a thin veneer over the surface of a flat platform of other rocks, or has there been a large relative rise in sea level which allowed the reef-building organisms to grow slowly upward on a pile of their own skeletal remains? This question has been debated for a hundred years.

In attempts to answer it, much was learned about atolls prior to 1946. But their geographic remoteness and the inadequacy of the available tools of investigation combined to limit this knowledge in most places to easily seen surface features.

In 1946, few American or European scientists had heard the name of Bikini Atoll. From 1946 to 1952, Bikini Atoll was studied intensively, from many different points of view and with modern tools of exploration, so that it has become perhaps the most thoroughly known atoll on earth. The papers included in this volume summarize and interpret this knowledge.

Planning for the scientific work on which this report is based began in the fall of 1945, shortly after it was decided to conduct tests of nuclear-fission weapons at Bikini Atoll. This decision had been made from rather little information, for Bikini, unlike neighboring Eniwetok and Kwajalein Atolls, had not been the scene of any major military activities in World War II. An accurate hydrographic chart of the lagoon and surrounding waters was needed for the safety of the many ships to be employed in the operation. Channels and anchorage areas had to be located and shore facilities established. Moreover, in order to gain a maximum of technical value from the weapons tests, a thorough understanding of the physical and biological environment of the proving ground was desirable. This was true particularly because the nuclear-fission explosions involved energy releases more comparable to those of large-scale geophysical phenomena than any previous man-made event. Likewise, the intensity of the nuclear radiation to be released was enormous, far greater than living organisms had ever experienced prior to 1945.

An advance task unit of survey and supply ships was sent to the atoll early in the spring of 1946. As one of its missions, this unit was to furnish living quarters, ships, small boats, aircraft, and other necessary support for a team of biologists, geologists, and oceanographers whose purpose was to carry out an integrated investigation of all aspects of the natural environment within and around the atoll: the currents and other properties of the ocean and lagoon waters, the surface geology, the identity, distribution, and abundance of living creatures, and the equilibrium relationships among all these. It was believed that these relationships might be disturbed by the nuclear-fission explosions and also by the introduction of large numbers of human beings and the mechanical equipment necessary for carrying out the tests. One of the problems posed was to separate these two kinds of disturbances. Accordingly, neighboring atolls were also to be investigated; these included Eniwetok Atoll where the preexisting environment had been altered by military activities, and Rongerik and Rongelap, which had scarcely been touched by the outside world.

The general responsibility for these studies of the environment was assigned to the Bureau of Ships of the Navy Department under the supervision of the writer and his associates in the Underwater Studies Group. Later, when Joint Task Force I was organized, this became the Oceanographic Section of the Task Force. The cooperation of universities, private research institutions, and several federal agencies was enlisted, including the Geological Survey, the Military Intelli-

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Note.—Contribution from the Scripps Instiution of Oceanography, New Series, No. 729.

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gence Division of the Office of the Chief of Engineers, the Smithsonian Institution, the Fish and Wildlife Service, the Woods Hole Oceanographic Institution, the University of California's Scripps Institution of Oceanography and Division of War Research, and the University of Michigan. Field work in biology, geology, and physical oceanography began early in March 1946 and continued until the end of August. Scientists responsible for different phases of the work were: H. S. Ladd and J. I. Tracey, Jr., surface geology of coral reefs and islands; K. O. Emery, submarine geology and sediments; C. C. Bates, beach studies; Gordon Riley, W. H. Munk, W. S. von Arx, and W. L. Ford, currents and diffusion in the lagoon, and water exchange between the lagoon and the open sea; E. C. La Fond, water temperatures and currents outside the atoll; M. C. Sargent and T. S. Austin, organic productivity; W. R. Taylor, land and marine plants; Leonard Schultz, lagoon and reef fishes; J. C. Marr and Vernon Brock, pelagic migratory fishes; J. P. E. Morrison, mollusks, birds, and land animals; M. W. Johnson, plankton. Project officers for the oceanographic section were Lt. Comdr. C. A. Barnes, USCGR, and Lt. Comdr. M. C. Sargent, USNR. The hydrographic survey ship, U. S. S. *Bowditch* (AGS-4), was headquarters for the scientific party. Other ships employed in the field work were U. S. S. *Sylvania* (KA *44*), U. S. *Blish* (AGS *10*), U. S. *Gilliss* (AGS *13*), YMS *463*, YMS *354*, YMS *358*, and ARS *8*.

Upon the arrival of Joint Task Force I in the test area two new phases of these investigations were undertaken: a seismic refraction survey of the atoll structure under the lagoon, carried out cooperatively by geophysicists of the Oceanographic Section and the Naval Ordnance Laboratory, and a reconnaissance study of the currents, temperatures, and salinities of the waters in the entire Marshall Islands area from latitude 20° N. to latitude 3° S. over a band of 20° in longitude. These observations were designed to extend and confirm both the large numbers of bathythermograph observations taken in the area during the war years and the very considerable pre-war hydrographic data collected (but not analyzed or published) by the Japanese. Comdr. B. Perkins, Jr., USNR, was the principal representative of the Oceanographic Section in the seismic studies; J. V. Atanasoff, M. B. Dobrin, and B. Snavely led the team of Naval Ordnance Laboratory geophysicists. The physical oceanographic reconnaissance of the Marshall Islands area was organized as part of the work of the Oceanographic Section by D. L. Bumpus, assisted by E. C. La Fond, G. C. Ewing, and H. Mann. Lt. Comdr. John Lyman, USNR, was project officer. Four destroyers of the patrol group were employed.

The primary responsibility of the late Vice Admiral W. H. P. Blandy, Commander of the Joint Task Force, and his deputy for technical direction, the late Rear Admiral W. S. Parsons, was to carry out the tests of nuclear weapons against naval vessels and other military equipment, but both leaders recognized the opportunity presented by Operation Crossroads to obtain basic scientific information. They and the technical director, Dr. R. A. Sawyer, wholeheartedly supported this aspect of the work of the Oceanographic Section.

In the spring of 1947, the writer was directed by the Joint Operation Crossroads Committee of the Department of Defense to organize a scientific resurvey of Bikini Atoll. This had as its primary purpose an investigation of any possible delayed or long-term effects of the radioactivity produced by the underwater nuclear explosion. Another objective was to undertake certain special geologic and biologic investigations needed to gain further understanding of the geologic history of the atoll. The most ambitious of these projects was the drilling of several deep holes on Bikini island (one of these was carried down to 2,556 feet) in order to gain further knowledge of the subsurface structure. This drilling was carried out by the George Failing Co., whose field superintendents were V. C. Mickle and E. Alexander. H. S. Ladd of the U. S. Geological Survey was scientific director of the drilling project. He was assisted by J. I. Tracey, Jr., of the Geological Survey, and Gordon Lill, of the Office of Naval Research. J. W. Wells conducted field investigations of the distribution and ecology of the corals of the atoll, and J. Harlan Johnson of the Geological Survey undertook similar studies of the calcareous algae. Dredging on the outer slopes of the atoll was carried out by R. D. Russell of the U. S. Navy Electronics Laboratory, assisted by E. H. Schuler of that laboratory. Preliminary work on the problem of solution of calcium carbonate in tide pools was undertaken by T. S. Austin, of the U. S. Navy Hydrographic Office, and T. Goro. Leaders of other scientific phases of the resurvey included Lawrence Blinks, Douglas Whitaker, G. M. Smith, and George Myers, all of Stanford University; Lauren Donaldson, of the University of Washington; and Lawrence E. Glendenin, of the Massachusetts Institute of Technology. Capt. C. L. Engelman, USN, was project officer for all technical phases of the resurvey; Dr. E. S. Gilfillan was technical director; and Capt. T. Hederman, USN, was commander of the task unit of three ships which carried out the expedition. The principal ship was the U. S. S. *Chilton*. Invaluable assistance in the drilling operations was given by a Construction Battalion detachment under Comdr. J. R. Denny, USN.

Study and analysis of the field results during the years following the resurvey emphasized the need for further information about the subsurface structures of the atoll and the adjoining Sylvania Guyot (Menard, 1952), and the character of the underlying rocks. This interest was heightened by an aerial magnetic survey of the atoll conducted cooperatively by the Geological Survey and the Naval Ordnance Laboratory, under the sponsorship of the Office of Naval Research, late in 1947.

Accordingly, in the fall of 1949, initial plans were laid to undertake a third oceanographic expedition to the area*, one of the aims of which was to make a seismic-refraction survey of the entire atoll, the guyot adjoining it, and the surrounding sea floor During the following 8 months, this objective was joined to the more general one of conducting a voyage of deep-sea exploration throughout the eastern and central basins of the North Pacific. Support was obtained from the Office of Naval Research and the Bureau of Ships of the Navy Department, and from the University of California through its Institute of Geophysics.

On July 27, 1950, the joint Scripps Institution of Oceanography-U. S. Navy Electronics Laboratory Mid-Pacific Expedition departed from San Diego aboard the research vessel *Horizon* of the Scripps Institution and the U. S. S. EPCE (R) *857* of the Navy Electronics Laboratory. On this voyage, the two ships traversed some twenty-seven thousand miles, partly in company and partly on separate courses. Both had returned to San Diego by November 1, 1950. Participating scientists included staff members of the U. S. Navy Electronics Laboratory, Scripps Institution of Oceanography, U. S. Geological Survey, Department of Meteorology of the University of California at Los Angeles, and the University of Southern California. The 2 ships spent 3 weeks in the Marshall Islands area from September 23 to October 10, 1950. The first part of this stay was occupied in establishing a camp and field laboratory on Bikini island, preparatory to a study of the interstitial waters of the island beaches and of diurnal changes in the tide pools of the beach rock and upper reef flats. Leaving the beach party ashore, the ships proceeded to Sylvania Guyot, where a program of bottom photography and bottom sampling, using sediment cores and rock dredges, was carried out. A series of cores was also taken down the southeast flank of Bikini Atoll into deep water about 60 miles from the southeast corner of the reef. K. O. Emery and J. D. Frautschy were in charge of the dredging and bottom-sampling operations, R. S. Dietz and Carl Shipek made the two remarkable bottom photographs which are among the illustrations in this volume, and R. Morita and R. F. Dill were in charge of the chemical studies of the reef and beach waters.

The final 10 days of the expedition's stay in the Marshall Islands area were spent by R. W. Raitt in making a seismic refraction survey of Bikini Atoll, Sylvania Guyot, and the surrounding sea floor. Dr. Raitt also succeeded in making a refraction profile of the southern part of Kwajalein Atoll.

The papers combined in this volume cover only a part of the scientific work at Bikini Atoll, Only those results are included which describe or help in understanding the structure of the atoll and the story of its building. The point of focus is the wonderfully detailed description given by Emery, Tracey, and Ladd of the atoll surface, both the visible portion near sea level and that which is hidden beneath the sea. To illuminate this picture fully, it is necessary to know as much as possible about the geologic and oceanic setting in which the atoll is situated.

Throughout the Marshall Islands area, sea mounts and atolls rise alone or in small groups from the abyssal sea floor. All the sea mounts examined by Emery, Tracey, and Ladd are guyots—that is they are flat on top as if sheared off by a gigantic plane. These guyots range in depth from 500 to nearly 1,000 fathoms. Examination by Gordon Macdonald of igneous rocks dredged from Sylvania Guyot and the deeper slopes of Bikini Atoll shows that the upper part of the guyot and the rock beneath the calcareous shell of the atoll is vesicular olivine basalt, typical of the central Pacific petrographic province but with a far higher percentage of pyroclastics than are found in Hawaii. Much of the volcanic glass is essentially unaltered, indicating that the eruptions which formed these peaks took place relatively late in geologic time.

The annual march of surface and subsurface water temperatures throughout the area, as shown by numerous bathythermograph observations, is described by Mrs. Robinson. A report on currents and physical properties of the waters has been prepared by Mao and Yoshida on the basis of observations taken during Operation Crossroads and prior to World War II by the Japanese. The ocean waters that bathe the uppermost outer slopes of the atolls are always clear and warm—more than 25 degrees C. Their empty blue reflects their poverty in living creatures; their high and uniform temperature down to depths of 300 feet or more is a complex result of the pattern of currents and winds, heat absorption, and evaporation. These in turn are controlled by the slow apparent meridional movement of the sun. The most striking features of the current pattern are the great tongue of the Equatorial Countercurrent, which flows from the southwest through the gap between the Marshall and Gilbert Islands, and the eddies north of this tongue east and west of the Marshalls. These eddies and the Equatorial Countercurrent must have played a major role in the initial distribution and continued resupply of the planktonic larval stages of reef animals throughout the islands.

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*Note.—Scientific parties concerned primarily with long-term biological effects of radioactivity visited the atoll in 1948 and 1949 but they did not undertake any geological or physical studies. See Hines, Neal O., Bikini Report, Scientific Monthly, Feb. 1951, pp. 102-113.

The scarcity of plankton in the ocean waters that supply the atoll reefs is described by M. W. Johnson in another of the papers of this work. This scarcity may account, in part at least, for the relative poverty of coral growth compared to that on the reefs in Fiji and the East Indies, and also for the fact, demonstrated by Sargent and Austin, that the reefs are more than self-supporting—that is, more organic matter is produced on them than is consumed.

As shown by Mrs. Robinson, the subsurface mixed layer of high uniform temperature is much deeper in the Marshall Islands area than farther eastward. Observations by the Mid-Pacific Expedition and the Pacific Oceanic Fisheries Investigations of the U. S. Fish and Wildlife Service (reported orally by O. E. Sette) show also that in the eastern North Pacific at these latitudes there is a comparatively rich plankton population and a high degree of biological activity. The accompanying turbidity must lessen the depths to which bright sunlight can penetrate. The deep mixed layer and the crystal clarity of the waters in the northern Marshalls may account for the considerable depths at which living reef corals are found. If the same conditions prevailed in the past, corals and calcareous algae could have withstood a much more rapid rate of submergence in the Marshalls area than in the regions to the east where the thermocline was shallower and the waters more turbid.

As shown by Von Arx, there is a continual fresh flow of ocean waters across the windward reefs that lie full in the path of the trade-wind swell. The waves, as they break, pile up water on the outer reef rim and this produces a pressure head which maintains the flow. Thus a continuous supply of dissolved nutrient salts, calcium, and carbon dioxide is furnished to the reef plants and animals. Under the bright sunlight, the plants respond by a vigorous photosynthesis resulting in a yearly production of nearly 7 tons of organic matter per acre, comparable to that of the most fertile Iowa cornfield. Most of this plant production is consumed by the reef animals and by the respiration of the plants. But about 12 percent of the total produced is excess organic matter and much of this may go to nourishing the animals of the lagoon.

Besides their role in supplying building materials to the reef plants and animals, the waves beating against the atoll affect the design and structure of the reef in other ways. Munk and Sargent point out that the size, length, and spacing of buttresses and channels on the outer margin directly reflect the average direction and force of the waves. These structures appear to be formed in accordance with the need to dissipate the destructive force of the trade-wind swell. Emery Tracey, and Ladd show that the widest living-reef margins and least steeply sloping reefs are those which breast this swell. On the leeward side, the reefs are narrow with nearly vertical outer slopes, whereas on the southern side, where the waters are usually calm but occasionally lashed by giant storm waves, the reef margin is broken and irregular and high boulder ramparts are built up around the islands.

Some of the calcium carbonate that was precipitated from the ocean waters by the reef organisms is being added as fine debris to the lagoon while the remainder must be slowly building up the outer slopes of the atoll as loose sediments and talus and as the solid reef wal which crowns the slopes. Both the amount of dissolved carbon dioxide and the solubility product of calcium carbonate are lowered by the high temperatures of the tropics, so that normal sea waters in low latitudes are supersaturated with calcium carbonate. Yet on the higher portions of the reef flat, and in the beach rock surrounding the islands, there is abundant evidence that solution of calcium carbonate is taking place Revelle and Emery found that above the normal high tide line calcium carbonate is being dissolved in pools of relatively fresh water. Below the high-tide line however, it is difficult to understand how limestones can be dissolved in the tepid salt water. Local solution beneath the algal mat that floors the reef pools and a diurnal fluctuation between conditions of calcium carbonate precipitation in the daytime and solution at night, in waters altered by the precipitation itself are suggested as possible answers to the dilemma.

The waters carried across the reef by wave-induced currents, and forced through the shallow passes by the combination of the North Equatorial Current and the wind, are trapped within the lagoon and only slowly escape in the tidal exchange through the deepe passes; Von Arx estimates that, on the average, a water particle stays in the lagoon for about 30 days During this time, it takes part in a slow rotary circulation, down wind in the surface layers, and from wes to east at depth. The lagoon waters, though somewha depleted of nutrient salts, are still capable of sustaining photosynthesis, most of which is carried out on th bottom by algae of the genus *Halimeda*. Sargent and Austin show that in the waters above the bottom th level of photosynthetic activity averages only abou a twentieth of that on the reef, about the same as in the ocean waters outside the atoll. Occasionally, however, as found by M. W. Johnson, a phytoplankton "bloom" occurs in the lagoon, no doubt facilitated by the slow rate of dispersion of the floating plants. That the over-all level of organic activity is higher in the lagoon than in the ocean waters outside the atoll is shown by Johnson's finding of a relatively large zooplankton population in the lagoon waters. Certain zooplankton organisms are endemic to the lagoon, but characteristic open-ocean plankton are also abundant there. These tiny animals maintain themselves within the lagoon by taking advantage of the rotary circulation of the water. Many of them apparently remain in the deep eastward-flowing water long enough to avoid being flushed out through the southwestern passes.

Despite the fact that organic activity within the lagoon is higher than in the open sea, the lagoon-dwelling organisms have evidently been incapable of depositing sufficient calcium carbonate to keep up with the post-Pleistocene rise of sea level. This is shown by the distribution of organic remains found on the lagoon floor by Emery, Tracey, and Ladd. In the deepest parts of the lagoon the green algae, *Halimeda*, are not now able to grow profusely, apparently because the intensity of light penetrating to these depths is insufficient. The shallowest parts of the lagoon floor lie in an outer zone next to the reef and are made up of fine debris which seems to have orginated largely from the skeletons of reef organisms. Elsewhere in the lagoon *Halimeda* remains are the most abundant constituent of the bottom sediments, except in some of the deepest areas where Foraminifera may be the chief constituent.

Many of the features of modern reefs evidently reflect the relatively rapid and large changes of sea level during and since the Pleistocene. The 8- to 10-fathom terrace around Bikini and neighboring atolls is one example; others may be the coral knolls in the lagoon, the deep channels, and the slightly higher level of reef rock under the islands.

Bikini Atoll appears, on the whole, to be a healthy, flourishing structure. Many of the varied assemblages of animals and plants that live on its reefs, in its lagoon, and on its outer slopes take calcium carbonate from sea water to build their shells or internal skeletons. When these organisms die some of them are buried in place but the hard parts of many others are broken up by wave action or riddled by boring organisms and the sediment thus produced is deposited in the lagoon or on the outer slopes of the atoll. The most important groups thus contributing to the atoll are the corals, the Foraminifera, and the algae. Samples obtained by drilling into the atoll show that these same groups have been building up the massive foundations of the present reefs at least since mid-Tertiary times.

A series of special reports on these organisms and the ecologic factors controlling their distribution has been prepared by John Wells, the late J. A. Cushman, Ruth Todd, Rita Post, Storrs Cole, and J. H. Johnson. At Bikini Atoll today the algae are the dominant organisms, particularly on the reef margins and over large parts of the lagoon. The corals are dominant over large areas of the reef and on the hundreds of knolls that rise from the lagoon floor. Indeed, more species of corals are now known from Bikini atoll than from any other area in the world. Since Bikini atoll lies far from the assumed centers of dispersal in the East Indies, this probably merely reflects the intensity of the collecting done at Bikini during the two seasons of Operation Crossroads. The Foraminifera thrive on the reefs today and their shells in many places make up the bulk of the beach sands. Other types occur in the deeper parts of the lagoon and on the outer slopes. The study of the ecology of the living forms was of great value in interpreting the conditions under which the older sediments were laid down.

The seismic-refraction studies of Bikini, Eniwetok, and Kwajalein Atolls, by Raitt, Dobrin, and Perkins, have confirmed and extended the results obtained by drilling, which show that several thousand feet of relatively unconsolidated calcareous materials overlie a volcanic core in these atolls. The irregularity of the old volcanic surfaces suggests that these cones may have been islands and that they were not truncated by wave erosion during the early stages of growth of the atolls. Seismic velocities show that a considerable thickness of unconsolidated material also lies inside the rim of Sylvania Guyot, and the question remains as to why this structure failed to participate in atoll growth. Lateral and vertical variations in seismic velocities reflect the complex construction of the old volcanoes. There is some evidence for downward bending of the crust beneath them, but the extent of the bending is relatively small.

Results of magnetic surveys by Alldredge and his associates are consistent with the picture obtained both by drilling and by seismic studies. Magnetometer surveys of other atolls may therefore be used with some confidence as a means of establishing the thickness of calcareous material. The loose and porous character of this material, which allows almost a free flow of sea water, is well illustrated by Swartz's comparison of the vertical-temperature gradient in the drill holes with that in the surrounding sea.

Origin and Accumulation of Aluminosilicates in the Ocean

By

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Origin and Accumulation of Aluminosilicates in the Ocean[1]

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Abstract

The basic assumptions used by B. Kullenberg in his attempt to calculate the probable magnitude of the variations of the rate of accumulation of clay appear unrealistic in the light of present knowledge, and consequently the results are hardly applicable. His assumptions imply that the sizes of the clay particles now observed in samples from the ocean floor have remained essentially unchanged during transport and deposition. Most probably, however, the marine clays represent the end product of precipitation and coarsening processes, the initial particles partly being of ionic and molecular size. Changes in the rate of deposition of aluminosilicates in eupelagic areas are rather determined by physico-chemical properties of sea water than by changes in the influx to the ocean. Such changes are supposed to be practically equalled out in the neritic and hemipelagic environment.

In a recent paper (1953), B. KULLENBERG has made an interesting attempt to estimate the maximum concentration of inorganic particles suspended in the open ocean. Kullenberg's calculation is based on the assumption that the approximate size distribution of the suspended mineral matter can be derived from the size distribution of the pelagic clay sediments. Knowing the effect of size and concentration of suspended particles on the scattering of light, Kullenberg uses measurements of the latter property, and arrives at an oceanic maximum concentration of $56 \cdot 10^{-6}$ g of solid matter per liter, or $21 \cdot 10^{-3}$ g in a column of 1 cm^2 cross section at average oceanic depth. Pointing to the fact that this amount is deposited in less than 300 years over a surface of 1 cm^2 in the calcareous part of the eupelagic area of the East Equatorial Pacific, Kullenberg demonstrates in an elegant way, that, provided his assumptions are valid and complete, the amount of fine terrigenous matter present in the sea is probably insufficient to act as a buffer against variations of supply during a major climatic cycle. He further claims that these variations were probably considerable, and that consequently changes in the rate of accumulation of terrigenous matter during the Pleistocene cannot be neglected, even in pelagic areas far away from the source of supply and characterized by great regional uniformity of this rate. Therefore, it does not appear feasible to Kullenberg to base an estimate of geological time in pelagic sequences on the assumption of a constant rate of accumulation of clay in eupelagic areas.

These conclusions are contradictory to those which can be drawn from the composition of Pleistocene eupelagic clay sediments as a

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function of time. The main constituents of these sediments are solid phases, formed in the ocean (marine hydrogenous matter, GOLDBERG 1954), further solids originating in the supramarine part of the hydrosphere and transported to the sea in suspension, and finally solid phases formed in the lithosphere (lithogenous matter, ibid.), and represented by igneous minerals such as finely divided quartz. Biogenous matter is of subordinate importance in the case of most pelagic clays.

If the rate of accumulation of any of the main constituents changes considerably, as supposed by Kullenberg, this will certainly be reflected by a corresponding change in their proportios in the sediment. The probability of simultaneous changes in the rates of accumulation of all phases, such that changes in the relative proportions were cancelled out, is exceedingly small. It ought therefore to be relatively easy to trace changes in the rate of accumulation of one phase or another by variation with time of the composition of the sediment. Such changes are, indeed, frequently recognized in shelf and hemipelagic deposits. Extensive rate changes in space and time also seem to be normal features of most pelagic sediment sequences in topographically irregular areas, and in environments with a considerable influx of turbidity currents (STETSON and SMITH 1938, PHLEGER 1951, ARRHENIUS 1952, ch. 2.39—2.48, RIEDEL 1952, CORRENS 1954). Under certain conditions, however, the changes in space and time of the rate of non-biogenous accumulation appear to be lowered to a small fraction of the rate value. These conditions seemingly are fulfilled in the eupelagic area of the East Equatorial Pacific (Arrhenius, l.c. fig. 1.0). Here the thickness of the Pleistocene strata (corrected for biogenous matter in the calcareous facies) is strikingly uniform, and the Pleistocene clay deposits so far investigated are characterized by considerable homogeneity with regard to the relative proportions of the inorganic components, thus indicating that no drastic changes in the rate of accumulation of single components took place in this area during Pleistocene time. A quantitative study of these conditions is being carried out at the present time, using the sediment cores collected from the East Equatorial Pacific during the Scripps Institution CAPRICORN Expedition of 1952—1953.

The relative uniformity of the rate of non-biogenous accumulation in the east eupelagic area of the Pacific Ocean may partly be explained by the large distance to the continents, the absence of islands, the smooth, rolling bottom topography, the low seismicity, and the presence further to the east of the East Pacific Rise, acting as a barrier to turbidity currents, released on the shelf slope. Even in the predominantly eupelagic parts of the East Equatorial Pacific, local depositional disturbances are found on topographic highs, where erosion sometimes occurs, and close to these localities, where the eroded material contributes to an abnormally high rate of accumulation (ARRHENIUS 1952, ch. 2.53). These effects appear, however, to be of only local importance, probably because the eroded, coagulated sediment in suspension forms aggregates which settle out again quickly enough to prevent transport over more than a few nautical miles.

The apparent disagreement between the observed evidence of low variability in Pleistocene time of the rate of non-biogenous accumulation in the east eupelagic area, on one hand, and Kullenberg's arguments on the other, still remains to be explained. To accomplish this we shall scrutinize the assumptions, on which Kullenberg has based his reasoning. The sedimentation model used by most earlier workers, including the present author (ARRHENIUS 1952) and KULLENBERG (1953) implies that the clay particles, observed in the eupelagic deposits, were transported to the site of deposition from the continental source without any essential changes in size and internal structure. Kullenberg, in accordance herewith, uses the grain size distribution of a recent pelagic clay to compute the size distribution of particles suspended in the ocean. A serious objection against this procedure arises from the fact that the mineral grains have to a large extent been cemented to aggregates, by hydrous oxides of manganese and iron. Many minerals further appear to have undergone secondary enlargement after deposition. This makes it highly doubtful whether the size distribution quoted by Kullenberg is in any way representative of the size distribution of the grains, even at the time when they crossed the water-sediment interface. Furthermore, the static model applied, which postulates an essentially unchanged size and internal structure of the particles from the moment of suspension to the moment of arrival to the sediment interface appears to be unrealistic in the light of recent investigations. CORRENS and v. ENGELHARDT (1938) have demonstrated that weathering proceeds by the breakdown of the parent mineral to ionic solutions and that the secondary minerals are reaction products of such solutions. A large fraction of the aluminum and silica, dissolved from continental rocks, is precipitated in the continental part of the hydrosphere or in the coastal areas of the ocean, but considerable amounts are carried in solution, even in the open ocean, and must be taken into account as a source of pelagic clay minerals. Dissolved silica is present in the sea in comparatively high concentration, and provides a steady source of reactive silicate ions. Analyses of the aluminum of sea water range between 3 and $2400 \cdot 10^{-6}$ g/l, the very high values reported from coastal waters (THOMPSON and ROBINSON, 1932; HAENDLER and THOMPSON, 1939; KALLE, unpubl., quoted by WATTENBERG, 1943; ISHIBASHI and FUJINAGA, 1951; SIMONS, MONAGHAN and TAGGART, 1953). For the sake of discussion we shall adopt a tentative figure for the open Pacific, and choose the conservative value of $10 \cdot 10^{-6}$ g/l Al. In addition to the dissolved aluminum a certain amount is present in particulate form, presumably as aluminosilicates. This amount is probably several times the mass in ionic solution. A concentration of particulate aluminum three times the concentration of dissolved aluminum is certainly a conservative estimate. The total amount of aluminum may thus be of the order of $40 \cdot 10^{-6}$ g/l. Although this figure may be far off from the true concentration, it is probably not too high, and it may be justified to use it for minimum computations. The concentration value used corresponds to $18 \cdot 10^{-3}$ g Al or $35 \cdot 10^{-3}$ g Al_2O_3 in a column of 1 cm² cross section at average depth, 4600 m, in the equatorial east eupelagic area of the Pacific. The mean concentration of Al_2O_3 in the eupelagic clay is 19 % by weight at 110° C and 17 % at the temperature and moisture conditions adopted in the work of the Swedish Deep Sea Expedition. Thus $18 \cdot 10^{-3}$ g Al will ultimately produce $206 \cdot 10^{-3}$ g of clay, i.e. ten times more than Kullenberg's estimate. With a rate of accumulation of $73 \cdot 10^{-3}$ g of clay per cm² in 1000 years (ARRHENIUS 1952, § 1. 2. 10) the period of turnover is at least 3000 years.

The aluminum bearing particles presumably have a particle size range from a few units of 10^{-8} cm to the order of magnitude 10^{-4} cm. Below the particle size 10^{-5} cm (MECKLENBURG, 1915) or $8 \cdot 10^{-5}$ cm (BECHHOLD and HEBLER, 1922) the scattering entirely follows Rayleigh's law, and the intensity of the scattered light of the Tyndall beam is thus a function of the third power of the diameter of the particles, the mass concentration of the solid phase being kept constant. Tyndall measurements, used as a basis for the determination of mass concentration, thus give far too low values, if Kullenberg's above mentioned assumption is applied with regard to the size distribution of inorganic suspended particles.

In order to arrive at a maximum figure for the concentration of the solid phase, Kullenberg allows the entire scattering observed to be regarded as due to inorganic particles. Considering the probably very small dimensions of most of these particles and the resulting weakness of the Tyndall effect, however, only a small fraction of the total scattering needs to be ascribed to inorganic matter, the main part of the Tyndall effect probably being due to plankton and organic detritus.

The mechanism of precipitation of aluminum in the sea has not yet been experimentally studied, but as the concentration in the ocean appears to be far below the solubility of aluminum hydroxide, it is believed that the primary solid phase consists of an aluminosilicate sol, which is progressively turning coarser by condensation and coagulation, and thereby settles out.

The concept of a marine origin of clay minerals is not a new one, but as far as the present author is aware, it has not been previously published or discussed in detail. Dr Josef Eklund at the Geological Survey of Sweden mentioned the idea in the early 1940's and the possibility of similar processes has recently been pointed out also by Dr George Bien at the Scripps Institution of Oceanography. The concept is in agreement with the results of GRIM, DIETZ, and BRADLEY (1949) on the properties of Pacific clay minerals. The formation of clay minerals in the marine environment has been demonstrated by NORIN's (1953) finding of authigenic illitic mica in sediments from the Tyrrhenian Sea. The mineral is confined to coarse-grained strata, where the water can circulate readily, and Norin points out that the authigenic illite is not derived from the detrital minerals, which are perfectly fresh, and that there is no relationship between the composition of the authigenic mineral and that of the surrounding detritus.

Even if the period of turnover of non-biogenous matter in the eupelagic area of the Pacific Ocean is 3000 years or a low number multiple of this value, instead of Kullenberg's value 300 years, this period is still short in comparison with a major climatic cycle. Following Kullenberg's reasoning there would under such circumstances be a close relationship between the rate of accumulation of clay in the eupelagic environment and the considerable changes, which he postulates in the rate of influx of source material of eupelagic clay. First, however, if the source material or a great part of it prevails in dissolved form, there is no need to assume large variations in the influx of such material to the ocean during the Pleistocene. Second, even large variations in the total influx of the reactive components may have a negligibly small effect on the concentration of these components in an advanced state of the reaction, i.e., after the lapse of such a time that the water mass in question has been transported far away from a coastal area. In a second order reaction, where, for the sake of simplicity, both reactants are regarded as identical, and enter the reaction in the concentration A_0, the concentration a found after a time t is expressed by

$$a' = \frac{A_0}{1+ktA_0},$$

where k under given conditions is a constant.

If the initial concentration were different from A_0 by a factor n, the concentration a'' at the time t would be

$$a'' = \frac{nA_0}{1+ktnA_0}$$

and thus the ratio between concentrations under these two conditions is:

$$\frac{a'}{a''} = \frac{\frac{1}{n}+ktA_0}{1+ktA_0} \qquad \lim_{t\to\infty} \frac{a'}{a''} = 1$$

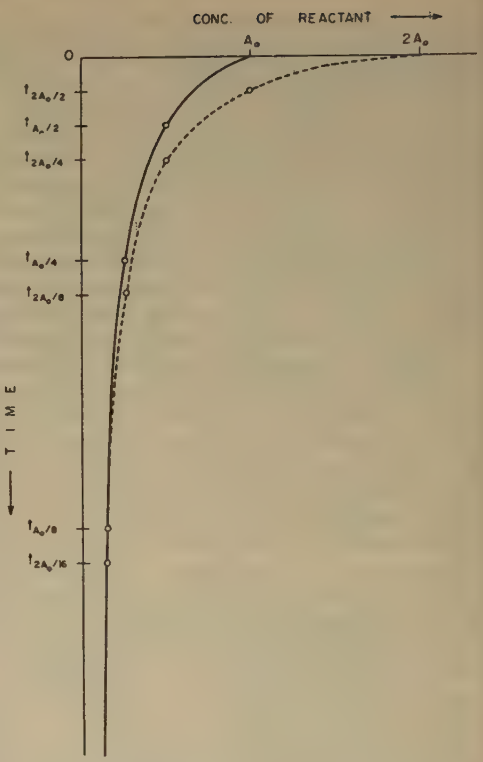

Fig. 1. Concentration as a function of time in a second order reaction. To simplify the example the reactants are regarded as identical. In the cases shown, the initial concentrations differ by a factor of two. The diagram illustrates the fact that the initial difference in concentration decreases rapidly with time, and that in an advanced state of the reaction the concentrations are practically equal in both cases. At a varying influx in the sea of suspended colloids or of dissolved thalassoxenic solids, large variations in the rate of precipitation can thus be expected in the coastal areas, close to river mouths, and negligible variations after a certain time of travel of the water mass containing the reacting system. Eupelagic conditions require that the uniformity of precipitation should be accompanied by uniformity of accumulation of the solid phase in question on the ocean floor.

$t_{A_0/2}$ indicates the first, $t_{A_0/4}$ the second, etc. half life of the reactants, in the case where the original concentration was A_0. $t_{2A_0/2}$, etc. are corresponding symbols for the case of the original concentration $2A_0$.

It is evident that the initial deviation of the ratio from unity is rapidly decreasing with increasing time and thus that differences in the initial concentration are practically eliminated in an early stage of the reaction. This is graphically illustrated in fig. 1. The rapidity of the elimination of these differences is still greater if the reaction is of higher order, which may very well be the case.

Similar relationships hold true also for the coagulation of particulate matter, which has been demonstrated by v. SMOLUCHOWSKI (1917) to be a second order reaction. Even if a considerable amount of the eupelagic clay is of supramarine origin it is thus possible to account for eupelagic uniformity of the rate of accumulation of clay, occurring togetner with large variations in the influx to the ocean. The main factor determining the eupelagic rate of accumulation of aluminosilicates appears to be the magnitude *k*, which is determined by the physico-chemical properties of sea water, and therefore probably subject to comparatively small fluctuations during the Pleistocene period.

This kinetic model is a deliberately over-simplified representation of the real conditions. The precipitation, condensation, and coagulation reactions in the ocean are most certainly much more complicated and heterogeneous than a simple second order reaction. However, such a simplified model appears to be useful and significant as long as the discussion is restricted to the question whether a buffer mechanism for the pelagic rate of precipitation can or cannot exist in the ocean.

It should further be pointed out that iron, titanium and zirconium on one hand, and the aluminosilicates on the other, appear to have different cycles in the sea (LEWIS and GOLDBERG, 1954, ARRHENIUS and BLOMQVIST, 1954). Although the uniformity of the titanium content of the eupelagic clay furnishes additional evidence of uniformity of the rate of accumulation of these two components, the validity of the use of titanium for dating purposes is obviously not directly connected to the question of the rate of accumulation of clay minerals.

The estimation of geological time from accumulated mass involves the approximation of a constant rate of accumulation. The error of age determination may largely be determined by deviation of this approximation from true conditions. Our knowledge of the average magnitude and the variance of this error is at present limited to the order of magnitude, and further studies of these factors are needed. Keeping in mind actual limitations of the method, it can, however, be used for the approximation of time factors and rate processes in the area and time interval in question. Although far from perfected, the procedure appears more reliable than previously available dating methods for the Pleistocene, which place the duration of this period between the probable limits 0.6 and 2 million years.

As some confusion appears to have arisen (BROTZEN, 1953) with regard to the significance of the uniformity in space and time of the rate of non-biogenous accumulation, it should be stressed again that the conclusions drawn by the present author apply only to the area and the time-rock units, where the indicative observations have been made, i.e., to the Pleistocene strata of the east eupelagic area of the Equatorial Pacific, and in a strict sense only to the cores from which the observations in question were derived. Large areas have been investigated (ARRHENIUS, 1952) where no such uniformity was found. It is therefore erroneous to regard the concept of uniformity of the rate in question as suggested for the entire ocean bottom.

From what has been said above, it is concluded that the indications of Pleistocene uniformity of the rate of accumulation of non-biogenous matter, observed, and so far observed only in the equatorial east eupelagic area of the Pacific Ocean, are in agreement with what is so far known and what can safely be postulated with regard to the mechanism of formation of pelagic deposits. Kullenberg's criticism deals with an improbable model of petrogenesis and does not take into consideration the reaction kinetics of the process of formation of marine sediments. Although it is an interesting and elegant attempt to treat one aspect of marine sedimentation, it does not, for the reasons given, apply to the pelagic environment.

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STATISTICS OF THE SEA SURFACE DERIVED FROM SUN GLITTER[1]

By

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ABSTRACT

Aerial photographs of the sun's glitter on the sea surface, taken under carefully chosen conditions in the Hawaiian area, were coordinated with measurements of winds (1–27 knots) from a vessel. Statistics of the glitter, interpreted in terms of the statistics of the slope distribution of the sea surface, gave the following results: (1) As a first approximation the slope distribution is found to be Gaussian; this can be accounted for by an arbitrarily wide *continuous* spectrum of ocean waves, but not by a spectrum consisting of a few discrete frequencies. (2) The ratio of the up/down-wind to crosswind components in mean square slope is less than two; this indicates a directional "beam width" in excess of 130° for the relatively short waves that contribute to the slope spectrum. (3) The mean square slope, regardless of direction, increases linearly with wind speed and reaches a value of $(\tan 16°)^2$ for a wind speed of 14 m sec^{-1}; this empirical relation follows in form and to an order of magnitude from a spectrum proposed by Neumann on the basis of wave amplitude observations. A spectrum proposed by Darbyshire cannot be reconciled with our observations.

Further results which have not been interpreted are: (4) An up- and down-wind skewness which increases with increasing wind speed is such as to make the most probable slope a few degrees rather than zero, with the azimuth of ascent pointing downwind. (5) A peakedness, which is barely above the limit of observational error, is such as to make the probability of very large and very small slopes greater than Gaussian. (6) Oil slicks laid by the vessel over an area of one quarter square mile reduce the mean square slope by a factor of two or three and eliminate skewness but leave peakedness unchanged.

The distribution of particle acceleration is closely related to the distribution of slope. Accordingly, the total mean square acceleration increases linearly with wind speed and reaches a value (at the surface) of $(0.4\ g)^2$ at a wind speed of 14 m sec^{-1}.

1. INTRODUCTION

If the sea surface were absolutely calm, a single mirror-like reflection of the sun would be seen at the *horizontal specular point.* In the usual case there are thousands of "dancing" highlights. At each highlight there must be a water facet, possibly quite small, which is so inclined

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as to reflect an incoming ray from the sun toward the observer. The farther the facet is from the horizontal specular point, the larger must be its slope in order to reflect the sun's rays back to the observer. The distribution in the glitter pattern is therefore closely related to the distribution of surface slopes.

In order to exploit this relationship, plans were laid in 1951 for coordination of aerial photographs of glitter from a B-17G plane with meteorological measurements from a 58-foot schooner, the REVERIE. The first measurements were made in July 1951 offshore from Monterey, California, where a variety of wind conditions could be expected. But one of the requirements for photographing the sun's glitter is sunshine. Unfortunately the number of clear days was even fewer than those given on climatological charts, hence only two successful flights were completed. Accordingly, plane and vessel were moved to Hawaii, where one can select radically different wind conditions by moving short distances. The island of Maui was chosen because the region surrounding this island is the least clouded in the Hawaiian area. Also, the harbor and airport facilities are conveniently near to one another. Conditions were excellent, and all observations were taken during the period 25 August to 25 September 1951.

Since the air borne instrumentation has been described by Cox and Munk (1954), we shall limit ourselves to a few comments on measurements from the vessel. Bendix Friez Aerovane anemometers were installed on the fore masthead (41 ft) and bowsprit (9 ft) of the REVERIE. At the time the aerial photographs were taken, the vessel would heave to, with the wind abeam, and be steadied by sails. With this arrangement the error inherent in using cup-type anemometers on a rolling vessel can be avoided. The output of the masthead anemometer and the difference between that and the bowsprit anemometer were smoothed by an R, C-filter with 18-second time constant and were recorded on two Esterline-Angus milliammeters. Wind direction was estimated by eye. For some of the earlier measurements we attempted to raise and lower a hand anemometer with the movement of boat and waves so as to keep it 3 ft above the water surface. Other measurements included air and water temperatures, and wet and dry bulb temperatures.

One of the objects of this investigation was a study of the effect of surface slicks. Early attempts to spray powdered Atco-grain detergent from vessel or plane were unsatisfactory. In the method adopted, oil was pumped on the water, the mixture consisting of 40% used crank case oil, 40% diesel oil, and 20% fish oil. With 200 gallons of this mixture, a coherent slick 2000 by 2000 ft could be laid in 25 minutes, provided the wind did not exceed 20 mph.

2. METHOD

Here we limit ourselves to a brief review of the method, since a full discussion is given by Cox and Munk (1954). Two pairs of aerial cameras, mounted in the plane, were wired for synchronous exposure. Each pair consisted of one vertical and one tilted camera with some overlap in their fields of view. One pair gave ordinary *image* photographs for the purpose of locating cloud shadows, slicks, and vessel; this pair also gave the positions of the horizon and the plane's shadow (to correct for the roll, pitch and yaw of the plane). The other pair of cameras, with lenses removed, provided *photometric* photographs. Sample photographs are shown in Figs. 1 and 2.

The method consists essentially of two phases. The first identifies, from geometric considerations, a point on the sea surface (as it appears on the photographs) with the particular slope required at this point for the reflection of sunlight into the camera. This is done by suitable grid overlays (see Figs. 1 and 2). Lines of constant α (radial) give the azimuth of ascent to the right of the sun; lines of constant β (closed curves) give the tilt in degrees. The grids depend on the elevation ϕ of the sun and on the orientation of the camera but not on the height of the camera. The effect of the setting sun is to concentrate the pattern along a narrow street (Fig. 1).

The second phase interprets the average brightness of the sea surface (darkening on the photometric negative) at various α,β-intersections in terms of the frequency with which this particular slope occurs. At the horizontal specular point the sea surface is apt to be so bright as to be blinding to the eye, whereas at some distance from this point the surface is much darker. The principal reason for this variation is that the gentle slopes (required for highlights near the horizontal specular point) occur more frequently than steep slopes. On the *density photographs* the glitter pattern appears as a round blob with a bright core (on the positive print) and a gradually diminishing intensity to the outside (Fig. 1, lower right). The density, D, of the blob on the negative is then measured with a densitometer at points which correspond to the intersection of appropriate grid lines. Factors other than the slope probability enter into the problem and have to be allowed for.

In addition to the reflection of the sun's rays from the sea surface, there are two other distinct sources of radiation: (1) the skylight reflected at the sea surface, and (2) the sunlight scattered by particles beneath the sea surface. We have attempted to correct for these. The disappearance of the glitter into this background imposes the essential limitation on the determination of the probability of large (and infrequent) slopes.

3. RESULTS

The results of these measurements are tabulated values of slope probability for various values of α,β. Instead of presenting these tabulated values we achieve compactness by giving the results in analytical form as a function of wind speed, thus bringing out the essential physical content. In this way the experimental error is also subdued. A reasonable approach is to make use of the fact that the distribution is close to Gaussian. By representing the data as a Gram-Charlier series we can develop the deviations from the normal distribution in a systematic manner. These deviations represent skewness and peakedness and therefore have a simple physical interpretation.

Some notation has to be introduced. Let x designate the crosswind coordinate, y the upwind coordinate, and z the elevation of the surface; furthermore, let β be the tilt and $m = \tan\beta$ the slope (regardless of direction) of a small element of sea surface, and let α be its azimuth of ascent to the right of the *wind* (not of the sun, as before). Then

$$z_x = \partial z/\partial x = m\sin\alpha, \qquad z_y = \partial z/\partial y = m\cos\alpha \tag{1}$$

are the crosswind and upwind components of slope. Since the mean sea level is nearly horizontal over large distances, it follows that the mean values of z_x, z_y (averaged over many waves) are zero. However, the mean values of z_x^2, z_y^2 do not vanish and will be designated by σ_c^2, σ_u^2. Hence σ_c, σ_u are the crosswind and upwind rms slope components. The corresponding "standardized" components are defined by

$$\xi = z_x/\sigma_c, \qquad \eta = z_y/\sigma_c\,. \tag{2}$$

Now let p be the probability of slopes. More precisely, let

$$p\,dz_x\,dz_y; \qquad p\,m\,d\alpha\,dm; \qquad p\tan\beta\sec^2\beta\,d\alpha\,d\beta$$

designate the probabilities that the slopes lie within the limits

$$z_x \pm \tfrac{1}{2}dz_x,\ z_y \pm \tfrac{1}{2}dz_y; \quad \alpha \pm \tfrac{1}{2}d\alpha,\ m \pm \tfrac{1}{2}dm; \quad \alpha \pm \tfrac{1}{2}d\alpha,\ \beta \pm \tfrac{1}{2}d\beta.$$

Which of these three equivalent forms is convenient depends on the particular problem under consideration. Our measurements show that p can be adequately represented by the expression

$$\begin{aligned} p = (2\pi\sigma_c\sigma_u)^{-1}\exp\left[-\frac{1}{2}(\xi^2+\eta^2)\right]\biggl\{1 &- \frac{1}{2}c_{21}(\xi^2-1) \\ &- \frac{1}{6}c_{03}(\eta^3-3\eta) + \frac{1}{24}c_{40}(\xi^4-6\xi^2+3) \\ &+ \frac{1}{4}c_{22}(\xi^2-1)(\eta^2-1) + \frac{1}{24}c_{04}(\eta^4-6\eta^2+3)\biggr\} \end{aligned} \tag{3}$$

for slopes up to $\xi = \eta = 2.5$.

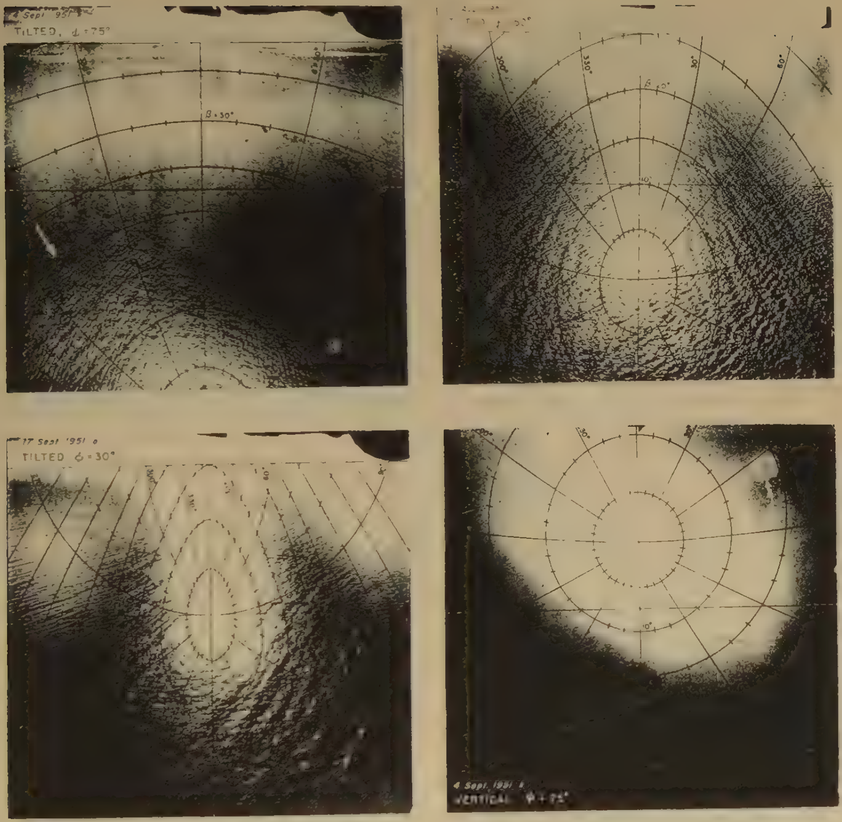
4 Sept '951
TILTED, φ = 75°
β = 30°
330°
30°
60°
300°
10°
17 Sept '951
TILTED φ = 30°
60°
30°
10°
4 Sept. 1951
VERTICAL φ = 75°

Figure 1. Upper Left and Right and Lower Left: The glitter pattern at solar elevations of $\phi = 75°$, $50°$ and $10°$ respectively. The superimposed grids consist of lines of constant slope azimuth α (radial) drawn for every 30° and of constant tilt β (quasi-elliptical) for every 5°. The vessel Reverie is encircled in upper left photograph. The white arrow indicates wind direction. Lower Right: Photometric photograph. Broken arrow indicates light circle due to Reverie.

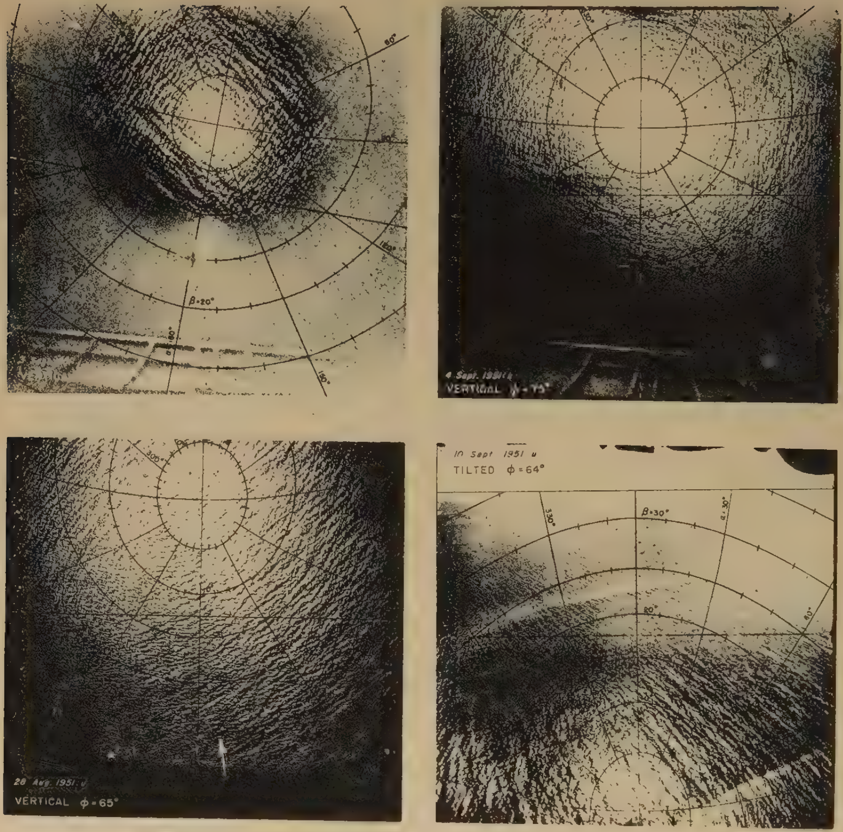
60°
β=20°
4 Sept. 1951 h
VERTICAL φ=73°
28 Aug. 1951 j
VERTICAL φ=65°
10 Sept 1951 u
TILTED φ=64°
β=30°
330°
30°
20°
60°

Figure 2. Upper Left and Right and Lower Left: The glitter pattern at wind speeds of 0.7, 3.9 and 14 m s -1 respectively. Large rotation of grid in upper left photograph is due to bad yaw as indicated by off-center position of plane's shadow (within white cross). Lower Right: A rectangular artificial slick, with near boundary almost through specular point. Brightness of slick sea surface is reduced for large β and somewhat increased for small β.

TABLE I

*Photograph Designation**	*Time†*	*Location of cameras*		*Wind*			*Temp. (°C) Sea Surface*
		N. Lat.	*W. Long.*	*Speed ms⁻¹*		*Direction*	
				41 ft#	*9 ft#*	*(true)*	
28 Aug. b	1106	21°01.8′	156°45.8′	11.6	9.6	060°	26.15°
28 Aug. p	1336	20°59.0′	156°44.0′	13.3	11.0	050°	26.4°
28 Aug. u	1403	20°58.2′	156°43.3′	13.8	11.6	050°	26.3
28 Aug. v	1403	20°58.2′	156°43.3′	13.7	11.5	050°	26.3°
3 Sept. j	1157	20°39.5′	156°46.6′	.72	.45	050°	26.51°
3 Sept. q	1330	20°39.5′	156°46.6′	8.58	7.11	120°	26.49°
3 Sept. t	1357	20°39.5′	156°46.6′	.89	.54	180°	26.51°
4 Sept. e	1126	20°40.2′	156°40.3′	1.79	.49	045°	25.90°
4 Sept. k	1158	20°39.0′	156°40.0′	3.93	3.58	100°	26.10°
4 Sept. n	1257	20°39.5′	156°36.9′	8.00	6.62	100°	26.20°
4 Sept. r	1324	20°40.0′	156°39.3′	6.30	5.27	111°	26.20°
4 Sept. v	1327	20°40.0′	156°39.3′	6.44	5.4	111°	26.20°
4 Sept. y	1353	20°39.5′	156°36.9′	4.92	4.07	110°	26.20°
5 Sept. b	1058	20°40.5′	156°35.7′	1.83	1.43	280°	26.6°
5 Sept. g	1124	20°40.1′	156°35.4′	1.39	.58	280°	26.7°
5 Sept. j	1354	20°46.8′	156°40.3′	3.35	2.99	225°	27.09°
6 Sept. c	1048	20°58.5′	156°45.3′	10.8	9.12	045°	25.95°
6 Sept. k	1124	20°58.0′	156°44.5′	10.2	8.85	045°	25.99°
6 Sept. q	1237	20°57.5′	156°44.0′	11.7	9.92	045°	26.3°
10 Sept k	1328	20°40.0′	156°38.3′	8.45	7.24	130°	26.60°
10 Sept. m	1333	20°40.0′	156°38.3′	7.15	6.00	130°	26.60°
10 Sept. r	1347	20°39.7′	156°39.3′	5.32	4.47	120°	26.59°
11 Sept. e	1317	20°45.5′	156°41.8′	5.45	3.75	210°	27.2°
11 Sept. f	1317	20°45.5′	156°41.8′	5.45	3.75	210°	27.2°
13 Sept. e	1308	20°17.6′	156°02.4′	2.41	1.97	090°	27.35°
13 Sept. f	1308	20°17.6′	156°02.4′	2.41	1.97	090°	27.35°
17 Sept. e	1136	20°29.9′	156°24.8′	9.79	8.31	086°†††	26.80°
17 Sept. c, h, k, n, q # #	1111 1205	20°28′	156°24′	9.74	8.18	088°†††	26.80°
17 Sept. A	1424	20°17.6′	156°14.8′	10.5	8.45	068°†††	26.90°

* Includes date of observation. 1951.

† Time meridian 150° W.

Elevation above sea level.

Probability distribution derived from 5 photographic sets.

Values of the rms slope components σ_c, σ_u are given in Table I together with other pertinent data. The values will be different under different wind conditions, and in general they will depend on whether the sea surface is, or is not, covered by oil.

Equation (3) can be interpreted geometrically as follows. Let the two horizontal axes designate z_x, z_y and let the vertical axis designate the value of $p(z_x, z_y)$. The bell-shaped surface $p(z_x, z_y)$ is high near the coordinate center (representing the high probability of small slope) and falls off in all directions. The total volume under the curve is unity. In the case of high winds this volume is low and wide; for low winds it is high and narrow. The volume of a prism centered at z_x, z_y

TABLE I

Temp. (°C) Air at 2m	*Humidity (%)*	*Significant waves*			*Sea Surface*	*χ +Sun Az* **	*Mean Square Slope Components*	
		Ht (ft)	*Period (sec)*	*Direction (true)*			σ_c^2	σ_u^2
28.0°	69	3.5	4		clean	063°	.0211	.0390
27.75	69	6	5	056°	clean	057°	.0294	.0484
27.5°	65	6	5	056°	clean	036°	.0287	.0452
27.5°	65	6	5	056°	clean	047°	.0276	.0404
29.0°	58	1.5	3	059°	clean	095°	.00337	.00489
28.75°	61	2	3	101°	clean	140°	.0224	.0230
29.0°	58	—	—	—	clean	***	.0152	.0153
27.2°	69	1	2	120°	Nat. slick	120°	.00096	.00126
27.9°	67	1	2	100°	clean	94°	.00694	.00977
28.0°	69	2	3	106°	clean	126°	.0136	.0191
28.0°	67	4	3	106°	clean	136°	.0134	.0170
28.0°	67	4	3	106°	clean	119°	.0136	.0186
28.0°	69	4	3	100°	clean	***	.0172	.0174
27.0°	68	3	4	160°	clean	296°	.00534	.00906
27.1°	67	3	4	104°	clean	280°	.00609	.00875
27.0°	65	5	4	140°	clean	237°	.0102	.0125
27.2°	69	4	4	045°	clean	***	.0252	.0265
					oil slick	***	.0111	.0108
27.2°	71	4	4	045°	clean	040°	.0254	.0357
27.2°	69	5	4	045°	clean	045°	.0254	.0374
26.8°	81	3	3	090°	oil slick		.0102	.0117
26.8°	81	3	3	090°	oil slick	***	.00860	.0100
27.2°	76	3	3	090°	clean	***	.0137	.0179
					oil slick		.00967	.00985
27.3°	71	2	3	120°	clean	***	.0136	.0137
27.3°	71	2	3	120°	oil slick	***	.0107	.0109
28.4°	60	4	5	075°	oil slick	***	.00391	.00467
28.4°	60	4	5	075°	oil slick	076°	.00724	.00959
27.8°	76	4	3	080°	clean	080°	.0209	.0264
					oil slick		.0106	.0126
27.7°	77	4	3	080°	clean	087°	.0230	.0322
27.8°	79	5	3	080°	clean	069°	.0224	.0365

** True Azimuth of principal (y') axis.

*** Observed wind direction used.

††† Wind direction estimated from direction of wind streaks on water; recorded wind direction appears to be in error by twice magnetic variation.

with a base area $\delta z_x \delta z_y$ is the probability $p(z_x,z_y)\,\delta z_x \delta z_y$ for the occurrence of slopes within $z_x \pm \frac{1}{2}\delta z_x$, $z_y \pm \frac{1}{2}\delta z_y$.

Now take sections along various directions through the coordinate center. Each of these is nearly Gaussian and can be closely fitted by a Gaussian curve of equal standard deviation. Two of these sections (the principal sections) are of particular interest (Fig. 3): for one the equivalent Gaussian curve has greater standard deviation than any other section; the reverse is true for the other. These correspond to the direction of the smallest and largest mean square slope. Our observations show that they are oriented crosswind and up/downwind.

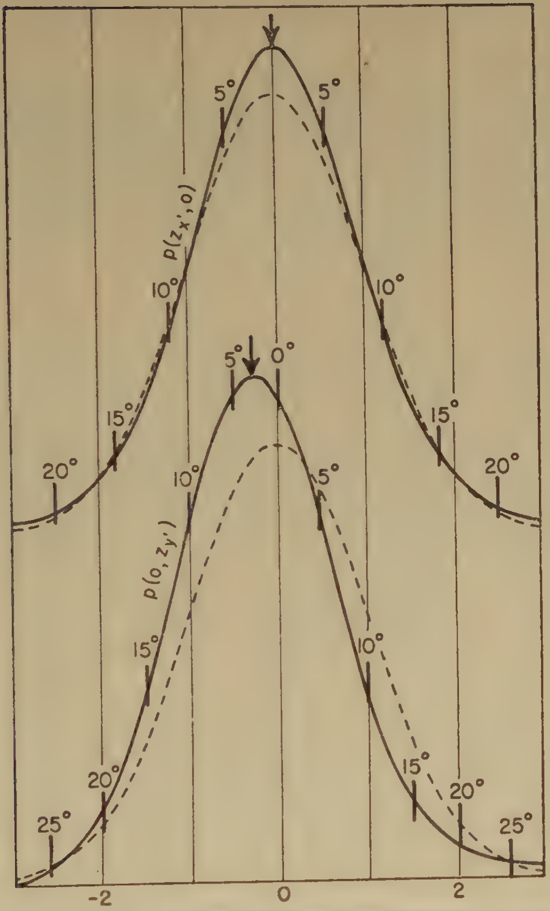

Figure 3. Principal sections through the probability distribution surface $p(z_x, z_y)$. The upper curves are along the crosswind axis z_x, the lower ones along the up/downwind axis z_y (positive upwind). The solid curves refer to the observed distribution, the dashed to a Gaussian distribution of equal mean square slope components. The thin vertical lines show the scale for both standardized slope components $\xi = z_x/\sigma_c$ and $\eta = z_y/\sigma_u$. The two scales for tilt, β, refer to a wind speed of 10 m sec^{-1}; skewness shown in the lower curve is computed for this wind speed. The modes are marked by arrows.

Another observed feature illustrated in Fig. 3 is an up- and downwind skewness. As a result, the most probable tilt is a few degrees, not zero, with the azimuth of ascent pointing downwind. Conversely, large slopes are more probable with azimuth of ascent pointed upwind. The skewness, as contained in the coefficients c_{21}, c_{03}, increases with increasing wind speed from nearly zero at very low winds to

$$c_{21} = -.11 \pm .03, \qquad c_{03} = -.42 \pm .12$$

at 14 m sec^{-1}.

The peakedness coefficients c_{40}, c_{22}, c_{04} are such as to make the very large and very small slopes more probable than those required for a Gaussian distribution (Fig. 3). The peakedness may be the result of variability in wind speed, but it is possible that systematic errors in the correction for background light may account for much of the observed peakedness. The peakedness coefficients show no significant variation with wind speed. The mean values are $c_{40} = .4 \pm .2$, $c_{22} = .1 \pm .05$, $c_{04} = .2 \pm .4$.

Oil slicks which cover an area of roughly one-fourth square mile reduce the mean square slope (regardless of direction) by a factor of two or three and eliminate skewness but leave peakedness unchanged.

There have been two other investigations of surface slopes. Duntley (1950) measured the surface slope components on Lake Winnipesaukee, N. H., by recording electrically the difference in immersion of pairs of thin vertical wires passing through the water surface. The wires were oriented to give simultaneous measurements of up/downwind and crosswind components. The separation between the wires on different occasions was 25 mm and 9 mm; consequently the measurements refer to the average value of slope over these distances. Schooley's (1954) observations from a bridge over the Anacostia River consisted of measuring the highlighted area on *resolved* photographs of the reflection of an artificial light source over the river. The results of their investigations agree in some points with ours, but there are significant discrepancies. Schooley's values of the mean square slopes are significantly *smaller* than ours for both high and low winds but agree at moderate wind speeds, whereas Duntley's values are 2.5 times *larger*. A discussion of these results has been given by Cox and Munk (1953).

4. SOME USEFUL RELATIONSHIPS

Of the many possible ways of describing the complexity of the sea surface, three in particular have been useful in modern work. Let f be some pertinent parameter with zero mean value such as elevation, slope, curvature, etc., and let $<f^2>$ be the mean square value (or variance) of f. According to the first approach, we let $\mathbf{T}_\omega \delta\omega$ be the contribution to $<f^2>$ by waves in the narrow, but not infinitely narrow (see Section 4.1), frequency band $\omega \pm \frac{1}{2}\delta\omega$. We can measure this quantity by recording it through an appropriate band pass filter, squaring the output, and averaging. It follows that

$$<f^2> = \int_0^\infty \mathbf{T}_\omega d\omega \tag{4}$$

is the mean square slope due to all frequencies. Here $\mathbf{T}_\omega$ is called the "frequency spectrum of the variance of f," or simply the spectrum.[2]

The second approach is the one we have taken. Let $p(f)df$ be the probability of slopes in the range $f \pm \frac{1}{2}df$. Then by definition

$$<f^2> = \int_0^\infty f^2 p(f)df. \tag{5}$$

Finally, a useful concept is the correlation (or mean displaced product)

$$\psi(a,b,\tau) = <f(x,y,t)f(x + a, y + b, t + \tau)> \tag{6}$$

between the value of f at position x,y and time t, and at $x + a$, $y + b$, and $t + \tau$. It is presumed that the surface is statistically uniform over time and space and that the corresponding averages are equal. For the special case $a = b = 0$, it can be shown (for example, see Rice, 1944: section 2) that the "auto correlation" is related to **T** according to

$$\psi(0,0,\tau) = \int_0^\infty \mathbf{T}_\omega \cos(\omega\tau)d\omega. \tag{7}$$

The foregoing equations show that the spectrum, the probability distribution, and the correlation are not unrelated. Our measurements of the probability distribution, therefore, have some bearing on the spectral representation of ocean waves. The required relationships, to be discussed (and made plausible, we hope) in this section, will be applied in the next.

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[2] For the special case where f denotes the elevation z above mean sea level, the terms "energy spectrum" and "power spectrum" have been used. Strictly speaking, the energy spectrum is $\rho g\mathbf{T}_\omega$, as $\rho g\mathbf{T}_\omega(\omega)\delta\omega$ is the energy contained in the band $\omega \pm \frac{1}{2}\delta\omega$. The term power spectrum was originally introduced in electrical problems where it is convenient to measure the energy spectrum by recording the power dissipated in a unit resistance. But it is not suitable to oceanographic problems. An appropriate definition would be $\rho g\mathbf{v}\mathrm{S}$, where $\mathbf{v}(\omega)$ is the group velocity vector and S the directional spectrum of z^2 (Section 4.2). Then $\rho g\mathbf{v}\mathrm{S}(\omega, \alpha)\delta\omega\delta\alpha$ is the flux of energy in the frequency band $\omega \pm \frac{1}{2}\delta\omega$ into the direction $\alpha \pm \frac{1}{2}\delta\alpha$. This important spectrum, after integration over all frequencies, gives the angular distribution around a cylindrical island of the dissipation of energy. In deep water the magnitude of $\mathbf{v}$ is proportional to wave period, and the true power spectrum is therefore weighted in favor of the low frequencies relative to the energy spectrum.

4.1 *The frequency spectrum of the variance of elevations.* Most observations of ocean waves have been made at a single point in space, say the point $x = y = 0$. The result has been a record of $z(0,t)$ for a limited time, $2T$. Such a record may be represented in two ways. Since we have no information concerning the sea surface before or after the record, we may assume (A) that it repeats itself indefinitely over successive intervals, $2T$, or (B) that it is zero before and after the record. These assumptions lead to (A) Fourier series with periods $(2T)$, $\frac{1}{2}(2T)$, $\frac{1}{3}(2T)$, $\cdots$, or (B) Fourier integrals with all possible periods. It can be shown that the two representations are exactly the same for those periods contained in the series. For our purpose it is more convenient to use the second approach. Hence

$$z(0,t) = \int_{-\infty}^{\infty} g(\omega)e^{i\omega t}d\omega, \qquad (8)$$

where

$$g(\omega) = (2\pi)^{-1} \int_{-T}^{T} z(0,t)e^{-i\omega t}dt \qquad (9)$$

is the (complex) amplitude of a wave train of frequency ω.

But $g(\omega)$ is not a convenient function. It is sensitive to phase and its absolute value tends to increase as the length of record $2T$ increases. On the other hand, $|g(\omega)|^2 = g(\omega)g^*(\omega)$ is not phase-sensitive. Furthermore, it is readily measured by passing the wave-generated signal through a narrow tuned filter. Since by hypothesis the sea surface is statistically uniform in time, the mean square of the sea surface elevation must exist. According to Parseval's theorem (Titchmarsh, 1937)

$$<z^2(0,t)> = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} z^2(0,t)dt$$

$$= \lim_{T\to\infty} 2\pi \int_{-\infty}^{\infty} \frac{g(\omega)g(-\omega)}{2T} d\omega = \lim_{T\to\infty} 4\pi \int_{0}^{\infty} \frac{|g|^2}{2T} d\omega. \qquad (10)$$

The last equality follows because z is a real quantity, hence from (9) $g(-\omega) = g^*(\omega)$.

The existence of the limit of the integral in (10) does not necessarily imply the existence of the limit of the integrand. It is tempting to assume that it does, for then the limit of $4\pi|g|^2/2T$ as $T \to \infty$ equals the spectrum $\mathbf{T}_\omega$ in accordance with (4). Surprisingly, this is not the case for waves which result from a large number of impulses randomly applied to the sea surface. A plot of $|\bar{g}|^2/2T$ against ω is then a wiggly line which oscillates more and more wildly as the record length is increased. The difficulty can be removed by defining $\bar{g}^2$ as a smoothed version of $|g|^2$ averaged over an arbitrarily small but *finite* range. The limit

$$\mathbf{T}_\omega = \lim_{T\to\infty} \frac{4\pi\bar{g}^2}{2T} \tag{11}$$

then exists, and equation (10) can be written

$$<z^2> = \int_0^\infty \mathbf{T}_\omega d\omega. \tag{12}$$

A rigorous mathematical approach[3] uses a Lebesgue integral formula in place of (10).

4.2 *The directional spectrum of the variance of elevation.* In contrast to measurements at a fixed point, the slope distribution was measured at a single instant. We may connect these two types of measurements by means of the wave equation. Suppose that z and $\partial z/\partial t$ are specified at $t = 0$ within the area $-S < x < S$, $-S < y < S$. Then

$$z(x,y,t) = \mathrm{Re} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(k_x,k_y) \exp i(k_x x + k_y y - \omega t) dk_x dk_y \tag{13}$$

satisfies the specified initial conditions, provided (Longuet-Higgins, 1950)

$$A(k_x,k_y) = \frac{1}{2\pi} \int_{-S}^{S} \int_{-S}^{S} \left(z - \frac{1}{i}\frac{\partial z}{\partial t} \right)_{t=0} \exp - i(k_x x + k_y y) dx dy. \tag{14}$$

Equation (13) represents z as a series of elementary wave trains of wave length $2\pi/k$, where $k^2 = k_x^2 + k_y^2$, frequency $\omega(k)$, phase velocity $C = \omega/k$ in the direction of the vector (k_x,k_y), and amplitude $A(k_x,k_y)$ $dk_x dk_y$. Each elementary train obeys the wave equation $\nabla^2 z = C^{-2}\partial^2 z/\partial t^2$. The sea surface has been assumed flat at $t = 0$ for $|x| > S$, $|y| > S$, and because of this assumption the forecasting value of (13) will deteriorate with time. This difficulty can be avoided by increasing the area $4S^2$ without limit. In particular, it can be shown (Cox and Munk, 1953) that if

$$\mathbf{S} = \lim_{S\to\infty} \frac{2\pi^2\bar{A}^2}{4S^2}, \tag{15}$$

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[3] See, for example, Wiener (1933). The application of the Lebesgue integral to ocean wave analysis is largely due to Pierson and his collaborators (Pierson and Marks, 1952).

where $\overline{A}^2$ is a smoothed version of $|A|^2$ (analogous to the relation between $\bar{g}^2$ and $|g|^2$), then

$$\psi(a,b,\tau) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S \cos\,(k_x x + k_y y - \omega\tau)dk_x dk_y. \tag{16}$$

The way is now open to find the connection between the frequency spectrum, $\mathbf{T}_\omega$, and the directional spectrum $\mathbf{S}$. Setting $a = b = 0$ and changing variables from (k_x,k_y) to (ω,α), we have

$$\psi(0,0,\tau) = \int_{0}^{\infty}\int_{-\pi}^{\pi} \mathbf{S}(\omega,\alpha)\left|\frac{\partial(k_x,k_y)}{\partial(\omega,\alpha)}\right| \cos\,(\omega\tau)d\alpha d\omega, \tag{17}$$

where $\partial(k_x,k_y)\partial(\omega,\alpha)$ is the Jacobian of the transformation. A comparison with (7) leads to

$$\mathbf{T}_\omega = \int_{-\pi}^{\pi} \mathbf{S}(\omega,\alpha)\left|\frac{\partial(k_x,k_y)}{\partial(\omega,\alpha)}\right| d\alpha, \tag{18}$$

which is the desired relation.

There are two approximations inherent in the stated form of the wave equation which limit the applicability of these results: (A) nonlinear terms have been neglected and (B) no allowance has been made for generation and decay of waves. The first error may be associated with the fact that the observed distribution of slopes showed a slight positive peakedness relative to a Gaussian distribution while the linear equation predicts a strictly Gaussian distribution for the statistically steady state. The second error will cause the predicted form of the sea surface to disagree with equation (13) for $t > 0$, but if the fetch and duration of the wind are large enough so that "equilibrium waves" are present, then the statistical behavior of the sea surface is sufficiently well represented. Since very short waves generate and decay most rapidly, the uncertainty of the results is greatest for large values of k and ω.

Note that the evaluation of the directional spectrum requires a knowledge of both z and $\partial z/\partial t$ at the initial time. Clearly the information $z(x,y,0)$ from a single snapshot could not tell us whether the waves are travelling in one direction or in the opposite one. Yet the topography shown on such a snapshot can be represented by a Fourier spectrum. We shall call this the *two-dimensional* spectrum. It differs from the *directional* spectrum inasmuch as it contains only directions in the range $-\frac{1}{2}\pi$ to $+\frac{1}{2}\pi$ as compared to $-\pi$ to $+\pi$. For any particular direction, α, the two-dimensional spectrum equals $\mathbf{S}(\alpha) + \mathbf{S}(\alpha + \pi)$. If the directional spectrum is narrow and contains only small contributions from directions outside $-\frac{1}{2}\pi < \alpha < +\frac{1}{2}\pi$, then the two spectra are nearly the same with regard to the surface elevation. However, the slight difference may be of importance at great depths where wave trains travelling oppositely lead to oscillations which Longuet-Higgins (1950) suggests are a cause of microseisms.

4.3 *Slope spectra and mean square slopes.* The relation (16) between the correlation and the directional spectrum permits a comparison of spatial observations (such as the slope distribution as determined by glitter observations) with records obtained at a single point. The starting point is equation (6), with f designating the elevation z. The method is to differentiate (6) and (16) with respect to a,b to obtain [4]

$$-\frac{\partial^2\psi}{\partial a^2} = \langle z_x(x,y,t)z_x(x+a,\, y+b,\, t+\tau)\rangle$$

$$= \iint_{-\infty}^{\infty} k_x^2 \mathrm{S} \cos(k_x x + k_y y - \omega\tau)\,dk_x dk_y \qquad (19)$$

$$-\frac{\partial^2\psi}{\partial b^2} = \langle z_y(x,y,t)z_y(x+a,\, y+b,\, t+\tau)\rangle$$

$$= \iint_{-\infty}^{\infty} k_y^2 \mathrm{S} \cos(k_x x + k_y y - \omega\tau)\,dk_x dk_y.$$

Comparison with (16) shows that $k_x^2\mathrm{S}$ and $k_y^2\mathrm{S}$ are the spectra of the slope components, z_x and z_y. For the case $a = b = 0$, equation (18) reduces to

$$\langle z_x^2\rangle = \iint_{-\infty}^{\infty} k_x^2 \mathrm{S}\,dk_x dk_y, \qquad \langle z_y^2\rangle = \iint_{-\infty}^{\infty} k_y^2 \mathrm{S}\,dk_x dk_y. \qquad (20)$$

With the y-axis pointing upwind, these are the crosswind and up/downwind components of mean square slopes σ_c^2 and σ_u^2. On changing to the variables (k,α), one obtains finally

$$\sigma_c^2 = \int_0^{\infty}\int_{-\pi}^{\pi} k^2 \sin^2\alpha\, \mathrm{S}k\,dk\,d\alpha, \qquad \sigma_u^2 = \int_0^{\infty}\int_{-\pi}^{\pi} k^2 \cos^2\alpha\, \mathrm{S}k\,dk\,d\alpha \qquad (21)$$

and

$$\sigma^2 = \sigma_c^2 + \sigma_u^2 = \iint_{-\infty}^{\infty} k^2 \mathrm{S}\,dk_x dk_y = \int_0^{\infty} k^2 \mathrm{T}_\omega\,d\omega. \qquad (22)$$

The last expression follows from (17) and (18).

[4] For example, see Eckart (1953): eq (37).

5. INTERPRETATION

The spectrum of the sea surface has been written in different ways by different authors. We now consider whether their mathematical models are consistent with our observations. First we seek to find the simplest model consistent with two observed features: the nearly Gaussian distribution of slopes (Section 5.1) and the appropriate ratio of up/downwind to crosswind mean square slope components (5.2). These features do not place any severe restrictions on the dependence of the slope spectrum on wave frequency. In Sections 5.3 and 5.4 the more complicated models proposed respectively by Darbyshire and Neumann are examined. Only the Neumann wave spectrum is consistent with the remaining principal features of the observed slope distribution: the linear increase of mean square slope with wind speed.

5.1 *Waves in one dimension.* The simplest model consists of a set of sinusoidal waves having one frequency and one direction. If such waves existed on the ocean surface they would have infinitely long crests. The slope distribution would be one-directional and the glitter pattern would consist of a single streak along some line α = constant. Clearly this is not in accord with the pattern shown on Figs. 1 and 2.

In addition to this discrepancy, the model leads also to frequency distributions of slopes which differ essentially from the observed distribution. The most probable slopes of a single sine wave are the slopes at the inflection points (say $\pm A$), where their values are stationary—and at a maximum. The probability $p(z_x)\delta z_x$ for slopes between $z_x \pm \frac{1}{2}\delta z_x$ is given by

$$\pi^{-1}(A^2 - z_x^2)^{-\frac{1}{2}} \tag{23}$$

for $z_x^2 < A^2$, and zero otherwise. The distribution is bimodal as shown in Fig. 4.

Next we consider the linear superposition of N sine waves

$$z_x = \sum_{j=1}^{N} A_j \cos (k_j x + \varphi_j). \tag{24}$$

We assume that the ratio of any two wave numbers, k_l/k_m, is irrational. The slope component is then an example of the "almost periodic function" of H. Bohr. As implied by its name, the almost periodic function comes close to being periodic but never quite repeats itself, a property which is in accord with our impressions of the real sea surface. The irrationality of the wave number forbids that equation (24) could represent any wave phenomenon in which the waves have rational "overtones," for example, Stokes waves of finite amplitude or seiches of a shallow rectangular body of water. In the open sea these are not believed to be serious limitations.

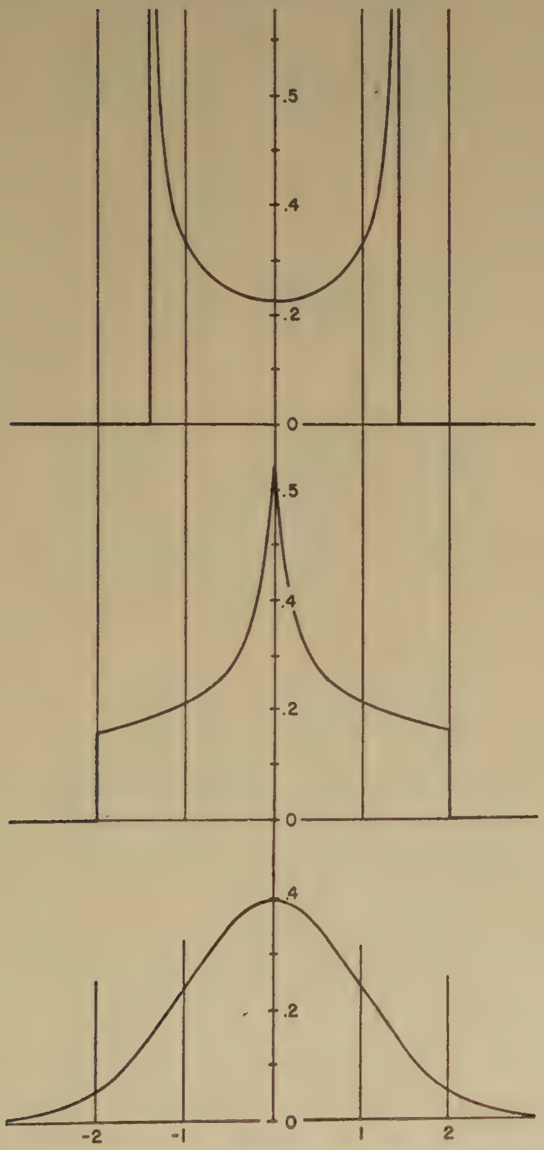

Figure 4. Top. Slope probabilities resulting from one sine wave. Middle. The linear superposition of two sine waves of equal maximum slope and irrational periods. Bottom. The linear superposition of an infinite number of irrational sine waves. The horizontal scale is $\xi = z_s/\sigma_s$; the vertical scale gives $p(z_s)$ in units of $1/\sigma_s$.

With the proviso of irrational wave numbers, the slope z_x due to any of the N components is uncorrelated with that of any other, and the calculation of the distribution of z_x is an example of the problem of random flights (for example, see Chandrasekhar, 1943). Cox and Munk (1953) found that

$$p(z_x) \doteq \pi^{-1} \int_0^\infty \cos(\rho z_x) \left[\prod_{j=1}^{N} J_0(\rho A_j) \right] d\rho. \tag{25}$$

For the special case of a single wave number ($N = 1$), this reduces to (23); for *two* waves of equal amplitude A, this reduces to

$$\pi^{-2} A^{-1} K[1 - (z_x/2A)^2]^{\frac{1}{2}} \tag{26}$$

for $z_x^2 < 4A^2$, and zero otherwise, where $K(x) = \int_0^{\frac{1}{2}\pi}(1 - x^2 \sin^2 t)^{-\frac{1}{2}}\, dt$ is the elliptic integral. In this case the distribution has a single logarithmically infinite maximum (Fig. 4). In the case of two unequal waves there would be two such maxima. For three sine waves there are no infinite peaks in the distribution function. In a general way it can be seen that the distribution approaches the Gaussian distribution as N increases. When N is large and when all N components are equal, equation (25) reduces to

$$(2\pi)^{-\frac{1}{2}} \sigma_x^{-1} e^{-\frac{1}{2}\xi^2} [1 - (\xi^4 - 6\xi^2 + 3)/(16N) + \cdots], \tag{27}$$

where σ_x^2 is the mean square slope and $\xi = z_x/\sigma_x$. This series is of the Gram-Charlier type, with the second term in the square bracket representing peakedness.[5] Comparison with equation (3) for the two-dimensional type reveals that the peakedness coefficient c_{40} is equivalent to $-(3/2N)$. Thus the foregoing expression leads to a negative peakedness, whereas the observed peakedness is positive. Hence the experimental results provide no evidence for discrete spectral components in the ocean waves.

A sea surface with a *continuous* spectrum of waves may be considered as the result of increasing the number N of discrete components without limit. In this case equation (27) reduces to a Gaussian distribution.

5.2 *"Beam width" of the trade wind sea.* In the preceding section we have learned that the observed distribution is consistent with a continuous spectrum in two dimensions. The next problem is to interpret the observed ratio σ_c^2/σ_u^2 in terms of the dependence of the directional spectrum **S** on the direction α. Clearly, if **S** were the same in all directions, then the crosswind and up/downwind slopes would

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[5] A similar development can be found in Syōno (1953).

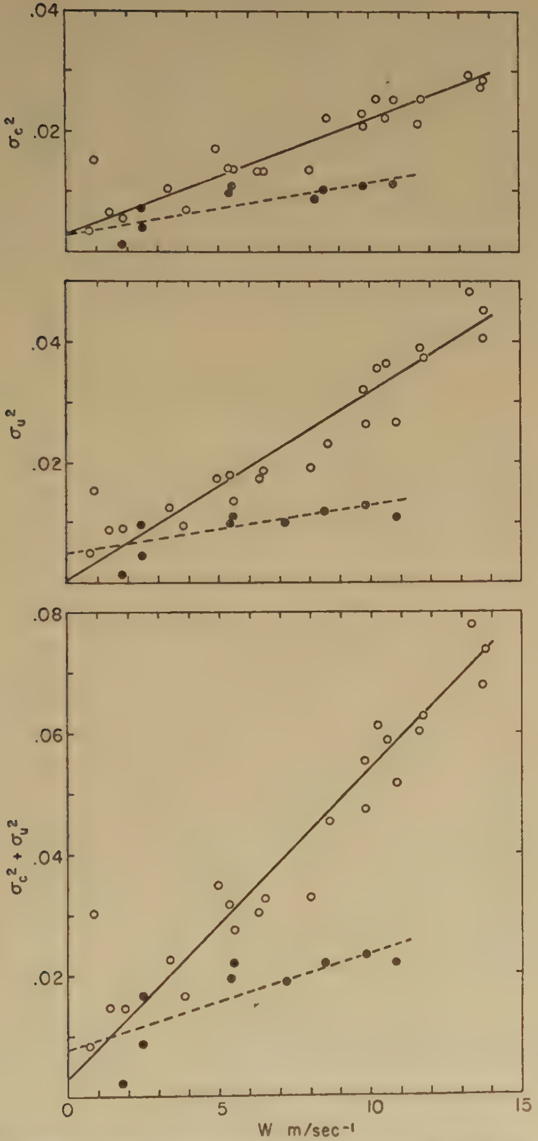

Figure 5. Mean square slope components and their sum as functions of the wind speed, W, measured 41 feet above sea level. The plot includes all analyzed data for clean sea surface (open circles) and slick surfaces (solid circles). Continuous lines are regression lines for clean surface; dashed lines for slick surface.

be equal and their ratio would be unity. On the other hand, if **S** were confined to a narrow range on both sides of the wind, then the crosswind component would be very small compared to the up/downwind component of mean square slopes. The measured values (Fig. 5, Table I) lie between these extremes and indicate a broad but nonetheless directional "beam pattern." The large variability in the ratio σ_c^2/σ_u^2 (Table II) is far in excess of experimental error. It is probably the result of differences, from one case to the next, in the variability of the wind direction. Steady winds would lead to small values in σ_c^2/σ_u^2, whereas gusty winds would diminish this ratio to somewhere near unity.

According to equation (21),

$$\frac{\sigma_c^2}{\sigma_u^2} = \frac{\int_0^\infty \int_{-\pi}^{\pi} k^2 \sin^2 \alpha \, \mathbf{S}(k,\alpha) k dk d\alpha}{\int_0^\infty \int_{-\pi}^{\pi} k^2 \cos^2 \alpha \, \mathbf{S}(k,\alpha) k dk d\alpha}.$$

The simplest assumption we can make is that the directionality is the same for all wave numbers, k, and that the beam pattern is sharply bounded at $\alpha = \alpha_0$. Hence

$$\mathbf{S} = F(k) \quad \text{for} \quad -\alpha_0 < \alpha < \alpha_0,$$

and zero otherwise. This gives

$$\frac{\sigma_c^2}{\sigma_u^2} = \frac{2\alpha_0 - \sin 2\alpha_0}{2\alpha_0 + \sin 2\alpha_0}, \tag{28}$$

as shown in Fig. 6. For a narrow beam the above function reduces to $\frac{1}{3}\alpha_0^2$.

For two infinitely narrow cross beams intersecting at an angle $2\alpha_0$, we set

$$\mathbf{S} = F(k) \quad \text{for} \quad \alpha = -\alpha_0, \qquad \alpha = +\alpha_0,$$

and zero otherwise. This yields simply

$$\sigma_c^2/\sigma_u^2 = \tan^2 \alpha_0. \tag{29}$$

TABLE II. Beam Widths and Angular Spread Between Two Intersecting Beams, Leading to Observed Ratios of Crosswind and Up/Downwind Slope Components

	Min.	*Mean*	*Max.*	*Slick (mean)*
σ_c^2/σ_u^2	0.54	0.75	1.0	0.86
$2\alpha_0$, single beam	134°	157°	180°	167°
$2\alpha_0$, two narrow cross beams	72°	82°	90°	86°

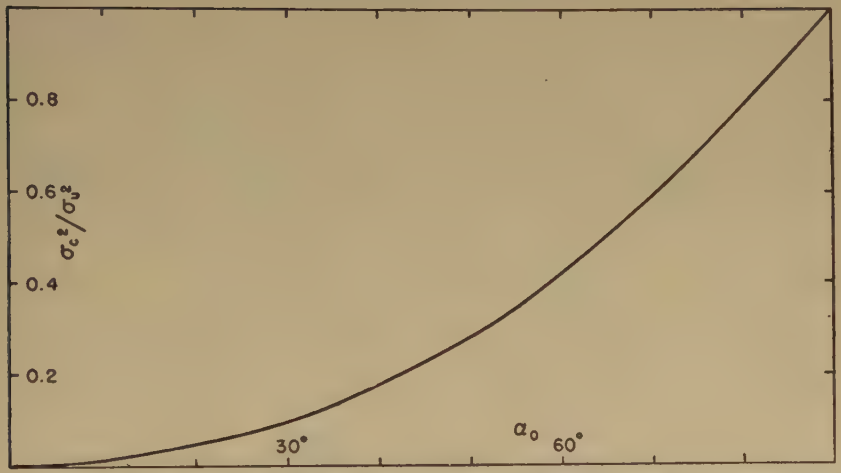

Figure 6. Half beam width of wave directions, α_0, as a function of the ratio of mean square slope components, σ_c^2/σ_u^2. It is assumed that waves of all periods have the same beam width.

The corresponding values are given in Table II. For a trade-wind sea, it is believed that the single broad beam conforms more nearly to actual conditions. The corresponding beam width is remarkably wide. For comparison, Duntley (1950) obtained $\sigma_c^2/\sigma_u^2 \approx 0.7$ on Lake Winnipesaukee, N. H.; Schooley (1954) obtained a smaller value, about 0.4, possibly because his photographs from a bridge over the Anacostia River sampled a relatively small area with a correspondingly smaller variability in wind direction. It should be kept in mind, however, that all of these values refer to those (high frequency) components of the spectrum that contribute largely to slopes. There are no other published measurements of the directionality of ocean waves, but preliminary results obtained by Barber (personal communication) by means of an array of wave *height* recorders indicate a beam width of 90°. This agrees exactly with Arthur's (1949) estimate based on a comparison between observed and predicted waves during the invasion of Sicily. However, it is becoming clear that the beam width varies considerably with meteorological conditions, so that a great deal of further work remains to be done.

5.3 *The spectra proposed by Darbyshire and Neumann.* The period spectrum[6] $\mathbf{T}_T$ is related to the frequency spectrum $\mathbf{T}_\omega$ by the relation

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[6] A choice of notation must be made between the use of frequencies and wave numbers on the one hand or of periods and wave lengths on the other hand. The physicist is more familiar with the former notation, the oceanographer with the latter.

$$\mathrm{T}_\omega|d\omega| = \mathrm{T}_T\,|dT|, \tag{30}$$

where $\omega = 2\pi/T$, $k = 2\pi/L$, and

$$\omega^2 = gk + \gamma k^3, \tag{31}$$

with γ designating surface tension divided by density (74 $\mathrm{cm}^3\ \mathrm{sec}^{-2}$ for clean water). According to (31), the phase velocity reaches a minimum value

$$C_{\min} = \omega_m/k_m = (4g\gamma)^{1/4} \tag{32}$$

when

$$\omega_m = (4g^3/\gamma)^{1/4}, \qquad k_m = (g/\gamma)^{1/2}.$$

Numerical values are $C_{\min} = 23\ \mathrm{cm\ sec}^{-1}$, $T_m = 0.074$ sec, $L_m = 1.7$ cm.

Waves much longer than L_m are gravity waves, and for these

$$\omega^2 \approx gk. \tag{32}$$

Waves much shorter are capillary waves, and

$$\omega^2 \approx \gamma k^3. \tag{33}$$

Darbyshire (1952) has proposed a spectrum of the variance of $z(0,t)$ equivalent to

$$\mathrm{T}_T = c'T^2 \exp\left[-2.0\left(\frac{gT}{U} - 4.6\right)^2\right], \tag{34}$$

where c' has the value 22 $\mathrm{cm}^2\mathrm{sec}^{-3}$ and U is the gradient wind speed equal on the average to 1.5 times the masthead wind speed, W.

The spectrum was obtained by frequency-analysis of pressure records of waves generated by local storms at Lands End, England. Only those storm records were analyzed for which the fetch was sufficient to generate equilibrium waves. The bottom pressure transducer was usually located at a depth of 50 ft. This requires that for wave periods less than 14 sec the usual hydrodynamic relationship must be used to convert bottom pressure to surface elevation, as has been done by Darbyshire. But for periods less than 6 sec, the bottom pressure oscillations are reduced to such a low level that this is no longer

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Most relationships are somewhat simpler in the former notation, but the integrals appearing in this section must actually be converted to the latter notation to be put into integrable form. We have made the following compromise. In sections dealing with the theory of spectra we have used the former notation. But in the following sections, where we are mostly concerned with numerical values of waves whose periods greatly exceed 1 second and whose lengths exceed 1 cm, it seemed preferable to adopt the latter convention.

practicable. Apparently these short-period waves have been ignored by Darbyshire. But it will be shown that these waves contribute about five-sixths of the total wave energy and that consequently Darbyshire's spectrum is too narrow and the total energy too small (Fig. 7). A pressure recorder at 50 ft is evidently not a suitable instrument for obtaining the energy spectrum.

On the basis of visual observations of fully developed waves in a storm area, Neumann (1953) proposed a spectrum (Fig. 5)

$$\mathrm{T}_T = \frac{1}{8}c\left(\frac{gT^2}{2\pi}\right)^2 \exp\left[-2\left(\frac{gT}{2\pi W}\right)^2\right], \tag{35}$$

where W is the wind speed and

$$c = 0.827 \times 10^{-3}\ \mathrm{sec}^{-1}. \tag{36}$$

It is of interest to compare the Darbyshire and Neumann spectra. The periods which correspond to the maximum value of T_T,

$$4.7\, g^{-1}U \approx 7.1\, g^{-1}W, \qquad 2\pi g^{-1}W \tag{37}$$

respectively, are in reasonable agreement. The mean square elevations,[7] however, follow different laws:

$$6.4 \times 10^{-5}\ \mathrm{cm}^{-1}\ \mathrm{sec}^3\ U^3, \qquad 3.2 \times 10^{-12}\ \mathrm{cm}^{-3}\ \mathrm{sec}^5\ W^5. \tag{38}$$

If the observations in Darbyshire's fig. 7 are fitted to Neumann's formula and if $<z^2>$ is computed as a function of W, we find that $c = 0.3 \times 10^{-3}\ \mathrm{sec}^{-1}$ compared to Neumann's value 0.8×10^{-3}. The small value presumably reflects the lack of information on wave periods less than $T_1 = 6$ sec. We propose to correct this value as follows. Assume Neumann's spectrum (35). The contribution of waves having periods greater than T_1 to the mean square elevation is

$$<z^2>_{T>T_1} = \int_{T_1}^{\infty} \mathrm{T}_T dT = \left(\frac{g}{2\pi}\right)^2 \frac{c}{8}\left\{\frac{1}{2}T_1{}^3V^2\left(1+\frac{3}{2}\frac{V^2}{T_1{}^2}\right)e^{-T_1{}^2/V^2} + \frac{3}{8}V^5\sqrt{\pi}\left[1 - H\left(\frac{T_1}{V}\right)\right]\right\}, \tag{39}$$

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[7] The average kinetic and average potential energy for gravity waves equal $\frac{1}{2}\rho g <z^2>$. The potential energy due to surface tension may be estimated as follows. The increase of surface area due to waves is $\int\int_A(\sec\beta - 1)dxdy$ and the potential energy per unit area is $(g\gamma/A)\int\int(\sec\beta - 1)dxdy \approx g\gamma\sigma^2/2$. The potential energy increases linearly with σ^2, hence it is proportional to wind speed and reaches a value of 2.8 erg cm^{-2} at $W = 14\ m\ \mathrm{sec}^{-1}$. According to the Neumann energy spectrum, this is 3×10^{-7} times the potential energy due to gravity waves under similar conditions.

where $V = \pi\sqrt{2}\, W g^{-1}$ and $H(\xi) = 2\pi^{\frac{1}{2}} \int_0^{\xi} e^{-t^2}\, dt$ is the error integral.

Entering equation (39) with appropriate values of W and $<z^2>_{T>T_1}$ from Darbyshire's data and setting $T_1 = 6$ seconds, we obtain $c = 2 \times 10^{-3}$ sec^{-1} with large scatter compared to the previous value of 0.3×10^{-3} sec^{-1} (uncorrected for the high frequency cut-off) and Neumann's value 0.8×10^{-3} sec^{-1}.

5.4 *The slope spectrum and mean square slope.* The mean square slope, regardless of direction, σ^2, can be computed from $\mathbf{T}_T$ according to equations (22) and (30). *Neglecting capillary waves*, the spectra proposed by Darbyshire and Neumann yield, respectively,

$$(2\pi)^4 \sqrt{\left(\frac{1}{2}\pi\right)}\, (4.6)^{-2}\, c'(gU)^{-1} = 1.0\, W^{-1} \tag{40}$$

$$\frac{1}{2}\pi^3 \sqrt{\left(\frac{1}{2}\pi\right)}\, cg^{-1}W = 1.6 \times 10^{-5} W. \tag{41}$$

By the method of least squares, our observations give

$$\begin{matrix} 5.12 \times 10^{-5}W + 0.003 \pm 0.004 \\ 1.56 \times 10^{-5}W + 0.008 \pm 0.004 \end{matrix} \tag{42}$$

for the clean and slick surface, respectively. Here W is in cm sec^{-1}.

Contrary to our observations, the Darbyshire spectrum predicts that the mean square slope *decreases* with increasing wind speed. For $W = 10$ m sec^{-1}, $\sigma^2 = 10^{-3}$ compared to the observed value $(54 \pm 4) \times 10^{-3}$. Clearly the spectrum proposed by Darbyshire has too little energy in the short waves. As noted earlier, this is not surprising, since waves having periods shorter than six seconds could not have been observed.

The important result is that Neumann's spectrum yields the observed linear relation between mean square slope and wind speed.[8] Furthermore, the computed proportionality constant agrees with the measurements over slicks, but it is one third the value required to account for the clean surface. If we take the value $c = 2 \times 10^{-3}$ sec^{-1} on the basis of Darbyshire's data (corrected for high frequency cut-off), the result is

$$\sigma^2 = 4 \times 10^{-5} W.$$

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[8] This fact was mentioned by W. Pierson in a paper delivered before the American Geophysical Union, May 1953.

A generalization of Neumann's spectrum of the form

$$\mathbf{T}_T \sim T^m \exp\left[-\left(T/W\right)^n\right]$$

yields

$$\sigma^2 \sim W^{m-3} \frac{1}{n} \Gamma\left(\frac{m-3}{n}\right),$$

and hence σ^2 will be proportional to W only if $m = 4$, as assumed by Neumann. Neumann states that his data are convincingly better in accord with $\mathbf{T}_T \sim T^4$ than T^3 or T^5. Of course there must be other analytic functions which also yield $\sigma^2 \sim W$. Nevertheless the consistency of Neumann's result with ours is encouraging.

Next we wish to examine whether or not an exact integration which considers capillaries leads to a measurable deviation from the linear relation between σ^2 and W. We assume without justification that Neumann's spectrum function can be extended into the high frequencies. The modification is such that for $T \ll T_m$ the slope spectrum decreases with decreasing T like $T^{8/3}$ instead of remaining constant (Fig. 7), so that the mean square slope must be less than that given by (41). It is no longer possible to obtain an integral in closed form. We derived analytic solutions for the two asymptotic cases, $W \ll c_{\mathrm{min}}$ and $W \gg c_{\mathrm{min}}$, and integrated the intermediary part by numerical methods. The resultant mean square slope is

$$\sigma^2\left[1 - 2.28\pi^{-\frac{1}{2}}\left(c_{\mathrm{min}}/W\right)\right] = \sigma^2 - 0.0005, \tag{43}$$

where σ^2 is the solution (eq. 41) when capillarity is neglected. The measured intercept (eq. 42) is $+\,0.003 \pm 0.004$. The modification is evidently smaller than the uncertainty in the empirical relations.

6. THE EFFECT OF SLICKS

We wish to consider whether it is possible to account for the observed reduction by a factor of two or three of the mean square slopes. The method will in a sense be the opposite of that in Section 4.2. There we assumed a statistical balance between generation and decay. Here we propose no generation and full decay by molecular viscosity.

According to Reynolds's classical theory (Lamb, 1932: 631–632), an inextensible surface film in effect annuls the horizontal velocity at the surface. This leads to a modulus of decay of

$$\tau = 2\sqrt{2}\,\nu^{-\frac{1}{2}}k^{-1}\omega^{-\frac{1}{2}},$$

where ν is the kinematic viscosity. In the actual case, the film will be somewhat extensible, and the foregoing expression may be regarded as an upper limit to the effectiveness of a surface active agent. The reduction in (amplitude)^2 for each spectral component is exp $(-\ 2t/\tau)$, where t is the length of time since the wave entered the slick. The time required to cross a slick of length S is $t' = Sk/\omega$, and the mean reduction (sampled by a photograph of the entire slick) is

$$F = \frac{1}{t'}\int_0^{t'} e^{-2t/\tau}\,dt = \alpha(1 - e^{-1/\alpha}),$$

where

$$\alpha = (2\omega)^{\frac{1}{2}}S^{-1}\nu^{-\frac{1}{2}}k^{-2} = 2.11 \times 10^{-4}k^{-2}\omega^{\frac{1}{2}}cgs$$

for a slick 500 m in length. For $\alpha \gg 1$, $F \approx 1$, and for $\alpha \ll 1$, $F \approx \alpha$. The two above equations with $\omega(k)$ lead to $F(T)$. This reduction factor has been applied to the (amplitude)^2 and (slope)^2 spectra, as shown in Fig. 7. For waves of 0.5 sec (1 ft length), these spectra are reduced by a factor of 100 (amplitude by a factor of 10), and thus waves shorter than this are essentially eliminated. This is in reasonable accord with visual observations. As is to be expected, the mean square amplitude is hardly affected by this "high frequency cut-off," whereas the mean square slope is appreciably reduced.

The mean square slope in the presence of slicks, $\int_0^\infty Fk^2\,\mathbf{T}_T\,dT$, equals

$$0.34 \times 10^{-2}, \qquad 0.76 \times 10^{-2}$$

for wind speeds of 5 m sec^{-1} and 10 m sec^{-1} respectively. The corresponding ratios in mean square slope with slick as compared to those with a clean surface are

$$0.40/0.82 = 0.48, \qquad 1.13/1.65 = 0.68.$$

The observations give

$$0.55, \qquad 0.44.$$

The numerical values show rough agreement between the observed decrease in mean square slope within the slick and that computed on the basis of Reynolds' classical theory. But some serious difficulties remain. Reynolds' theory presumes a (horizontally) inextensible surface film such as one would expect to find for a monomolecular layer or for layers a few molecules thick at most. On the other hand, the thickness of the artificial slicks is estimated to be of the order of 10^{-4} cm, or 1000 molecules. This estimate follows from considerations involving the known size of the slick and of the volume of oil and from the occasional appearance of interference colors.

It is possible, however, that the oil film had an adsorbed monolayer at the air-oil or oil-water interface.[9] The compressional strength of

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[9] See also Hennicker (1949). He summarizes experimental evidence for crystal-like organization of polymolecular films. Such a film would be expected to withstand static forces.

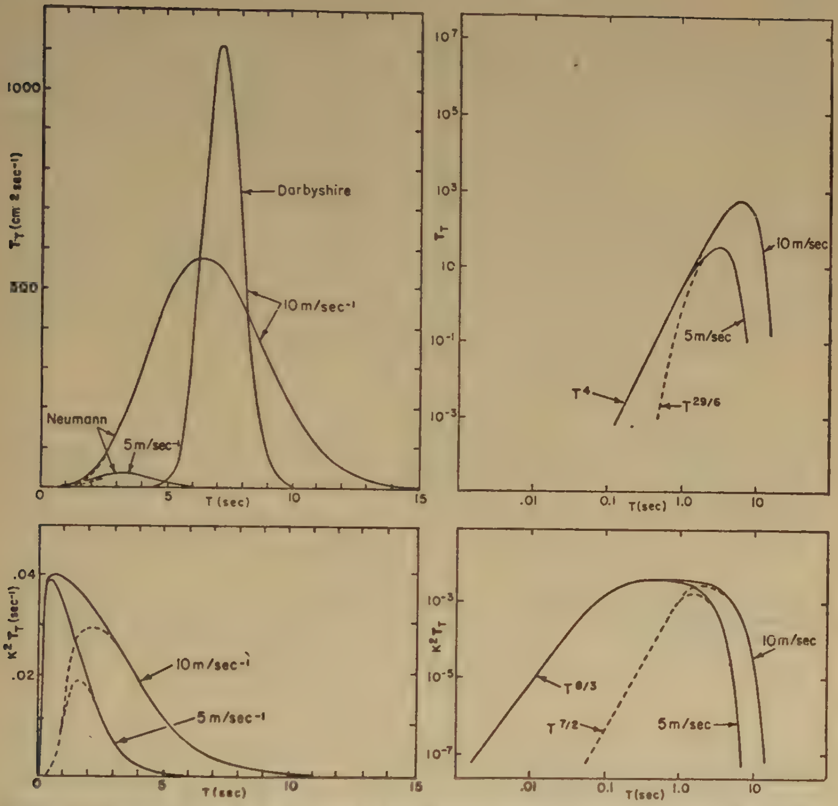

Figure 7. Period spectra of variance of sea surface elevation (upper panels) and of slope regardless of direction (lower panels). The left panels are drawn on a linear scale, the right panels on a double logarithmic scale. The asymptotic behaviour for high frequencies is indicated. Curves refer to wind speeds of 5 and 10 m sec^{-1} as noted. Solid lines apply to clean sea surface, dashed lines to slick surface. The variance of the $z(t)$ spectrum proposed by Darbyshire is illustrated on the upper left panel; all other curves are derived from Neumann's spectrum.

such a layer would be the difference between the surface tension of a clean interface ($\approx$ 40 dynes cm^{-1} for oil-water) and the surface tension of the contaminated surface ($>$ 0 dynes cm^{-1}). The following calculation shows that this would not be sufficient to annul the surface orbital velocities.

The x,y components of stress induced in the film by horizontal shear in the orbital velocity just below the film are

$$p_{xz} = \mu\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right), \qquad p_{yz} = \mu\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right),$$

where u,v,w are the x,y,z components of orbital velocity of the waves, μ is the viscosity, and the derivatives are to be evaluated at the surface. Let $\mathbf{p}$ be the vector shear whose components are p_{xz} and p_{yz}. For an infinitesimal wave train in the direction $\mathbf{k}$ (unit vector $\mathbf{k}_1$) of elevation

$$Re\,\{A \exp\,[i(kr - \omega t)]\}kdkd\alpha,$$

the appropriate formula is (Lamb: Arts. 349, 351)

$$\mathbf{p} = \mathbf{k}_1\omega^{3/2}(\rho\mu)^{\frac{1}{2}}\,Re\,\left\{A \exp\left[i\left(\mathbf{k}\cdot\mathbf{r} - \omega t - \frac{\pi}{4}\right)\right]\right\} kdkd\alpha.$$

Consider two points, $\mathbf{r}_1$ and $\mathbf{r}_2$, and let $\Delta\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$. Then, if there is no shear strength in the film, the scalar

$$F_{12} = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{p}\cdot d\mathbf{r}$$

is the *difference* in tension between the two points. For the wave train, this gives

$$F_{12} = 2\omega^{3/2}\,(\rho\mu)^{\frac{1}{2}}\,k^{-1}\sin\,(\tfrac{1}{2}\mathbf{k}\cdot\Delta\mathbf{r})\quad Re\left\{A \exp i\left(\mathbf{k}\cdot\mathbf{r} - \omega t - \frac{\pi}{4}\right)\right\} kdkd\alpha.$$

For a continuous spectrum of waves, the mean square tension can be shown to equal

$$<F_{12}^2> \;=\; 4\rho\mu \iint \omega^3\,k^{-2}\sin^2\,(\tfrac{1}{2}\mathbf{k}\cdot\Delta\mathbf{r})\,\mathrm{S}kdkd\alpha.$$

For sufficiently large values of Δr, the $(\sin)^2$ factor, which oscillates rapidly, may be replaced by its average value, $\frac{1}{2}$, and the integration over α may be performed:

$$<F_\infty{}^2> \;=\; 2\rho\mu \int_0^\infty \omega^3\,k^{-2}\,\mathrm{T}_T dT.$$

Assuming the Neumann spectrum for T_T, and setting $\omega^3k^{-2} = g^2T/2\pi$, (gravity waves) yields

$$<F_\infty{}^2> \;=\; \rho\mu\,\frac{(2\pi)^3cW^6}{32\,g^2} = 6 \times 10^7\left(\frac{W}{10\text{ m sec}^{-1}}\right)^6 (\text{dyne cm}^{-1})^2.$$

The required strength is therefore far in excess of 40 dynes/cm. But the large value reflects primarily the stresses due to the long period waves. To estimate the longest waves which will not readily rupture the film, we may set

$$2\rho\mu \int_0^{T_{\max}} \omega^3k^{-2}\mathrm{T}_T dT \;=\; (40\text{ dyne cm}^{-1})^2.$$

Neglecting capillary waves, this gives

$$T_{\max} = (24)^{1/6}(2\pi)^{\frac{1}{2}}(\rho g^4 \mu c)^{-1/6}(40 \text{ dyne cm}^{-1})^{1/3} = 0.7 \text{ sec.}$$

The principal reduction in σ^2 by slicks has been attributed to waves of period greater than 0.7 sec (Fig. 7).

No allowance for generation and decay (other than by molecular processes) has been made in the present calculation. An alternate hypothesis for the effectiveness of slicks is that they damp only high frequency wave components and that, in absence of these components, the balance between generation and decay is thrown in favor of decay for low-frequency components. This matter needs further investigation.

7. THE SPECTRUM OF ACCELERATION

The horizontal acceleration of an elementary wave train, $A \cos (kx - \omega t)$, has an amplitude $\omega^2 A$ at the sea surface. For gravity waves this equals gkA. The slope has an amplitude kA. Except for a minor contribution from capillaries (see end of Section 5.4), *the distribution of acceleration (in units of g) and of slope (in radians) are equivalent:*[10]

$$a_c^2 = \sigma_c^2, \qquad a_u^2 = \sigma_u^2,$$

where a_c^2 and a_u^2 are the crosswind and up/downwind components of the mean square acceleration (in units of g) at the sea surface. The mean square horizontal acceleration, regardless of direction, is therefore

$$a_h^2 = a_c^2 + a_u^2 = \sigma^2.$$

The mean square vertical acceleration a_v^2 for deep water waves equals the horizontal acceleration, and the mean square acceleration in all three directions is

$$a^2 = a_h^2 + a_v^2 = 2\sigma^2.$$

Preceding results regarding the slope distribution can be applied directly. Thus the up/downwind component exceeds the crosswind component of mean square acceleration by a factor of 1.3, on the average; all mean square accelerations increase linearly with wind, and the total rms acceleration at a wind speed of 14 m sec^{-1} is 0.4 g!

The horizontal acceleration spectrum is $\omega^4 \mathrm{T}_T$, and the mean square acceleration,

$$a_h^2 = \int_0^\infty \omega^4 \mathrm{T}_T dT = \pi^3 \sqrt{\left(\frac{\pi}{2}\right)} \frac{cW}{2g},$$

varies *exactly* in proportion to wind speed according to the Neumann spectrum.

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[10] This was first pointed out to us by N. F. Barber (personal communication).

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The Effect of Marine Bacteria on the Development and Hatching of Pelagic Fish Eggs, and the Control of Such Bacteria by Antibiotics[1]

CARL H. OPPENHEIMER[2]

THE occurrence of bacteria in the sea is widespread. ZoBell (1946) has reported an average of 1,000 bacteria per ml. in surface waters near shore. Such concentrations of bacteria may influence fishes by the liberation of proteolytic enzymes, by formation of toxins, or by the invasion of muscle, alimentary tract, and fins. Few investigators in marine microbiology have attempted to determine the significance of bacteria in the life cycle of marine fishes. Most of the fragmentary accounts refer merely to microorganisms that have caused the death or lesions on fishes (Plehn, 1924; Wells and ZoBell, 1934; Nigrelli, 1940; Rucker, 1949; Hodgkiss and Shewan, 1950).

Studies involving the relationship between bacteria and the life cycles of fishes are usually difficult and have been heretofore relatively little attempted. The tendency of marine bacteria to stick to solid objects (ZoBell and Allen, 1933) complicates experimentation. In determining the effect of marine bacteria on living organisms, the primary difficulty is to minimize contaminations. This problem is acute in the study of marine fishes because most of the agents used to decrease the bacterial population are also harmful to the fishes (Wells and ZoBell, 1934).

Of the several antibiotics that were employed in a recent study (Tarr, Southcott, and Bissett, 1950), aureomycin and terramycin were most effective in reducing the bacterial content of fishes during storage. At a concentration of 50 parts per million (ppm) these antibiotics did not inhibit all the bacteria but did decrease the total number which usually accumulated during fish storage. Spencer (1952) used antibiotics to decrease the bacterial population in studies with marine algae with reasonable success. These results suggested that antibiotics might

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[1] Contribution from the Scripps Institution of Oceanogra-hy, New Series, No. 732.

[2] Research conducted in part as a Fulbright Fellow in arine microbiology in Norway, 1952–53.

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TABLE I

NUMBERS OF VIABLE BACTERIA PER ML. OF SEA WATER FROM OSLOFJORD, NORWAY, CONTAINING DIFFERENT CONCENTRATIONS OF ANTIBIOTICS, INCUBATED AT 18°C., AND TESTED AFTER 12, 24, AND 72 HOURS INCUBATION

Antibiotic	Conc., ppm	Number of viable bacteria		
		12 hours	24 hours	72 hours
Penicillin	25	4,500	16,000	45,000
	50	2,700	900	43,000
	100	1,700	6,000	75,000
Neomycin	25	370,000	320,000	200,000
	50	45,000	33,000	170,000
	100	6,000	18,000	270,000
Strepto-mycin	25	20,000	30,000	47,000
	50	10,000	62,000	110,000
	100	10,000	72,000	330,000
Chloro-mycetin	25	5,500	15,500	120,000
	50	2,700	16,000	2,000
	100	600	13,000	1,500
Control (no antibiotic)	...	2,200,000	1,500,000	600,000

reduce the bacterial content in sea water cultures of fish eggs.

This paper is concerned with a comparison of the number of pelagic fish eggs which hatch in the presence and absence of marine bacteria. The experiments were conducted in two widely separated regions, namely southern California, U. S. A., and Oslofjord, Norway. Data are included relative to the possible use of combinations of antibiotics that reduce the bacterial content of sea water.

METHODS AND MATERIALS

Several antibiotics were tested, alone and in combinations, for their ability to reduce the bacterial population of sea water. The antibiotics (Tables I–III) were water soluble compounds purchased locally from medicinal stocks, excepting those marked and acknowledged as samples. Weighed amounts of the antibiotics, corresponding to final concentrations of 25, 50 and 100 ppm, were added to sterile 250-ml. flasks containing 100 ml. of sea water. The sea water was collected from the end of the 1,000-foot pier at the Scripps Institution of Oceanography and at Huk, Bygdøy Island in Oslofjord, Norway. Before the sea water was added to the flasks, and thereafte at frequent intervals during the incubatio period, the numbers of viable bacteria per ml were determined by standard dilution an plating methods. The data recorded from plat ing procedure are the averages from duplicat tests. In this procedure colony counts wer made after 6 days incubation at 20°C. In al instances the original antibiotic solutions wer diluted more than 1:100 during the platin procedure, which tended to reduce their residua effect during colony formation. The dilutio water consisted of a sterile mixture of 75 pe cent (by volume) sea water and 25 percen

TABLE II

PLATE COUNT ESTIMATES OF NUMBERS OF BACTERIA PER ML. OF ANTIBIOTIC-TREATED SEA WATER AFTER DIFFERENT PERIODS OF TIME

The sea water was collected near La Jolla, California

Antibiotics, 50 ppm	Number of viable bacteria per ml.		
	12 hours	24 hours	144 hours
None (control)....	3,000	1,000,000	2,000,000
Aureomycin HCl..	100,000	100,000	2,000,000
Terramycin HCl..	40,000	100,000	60,000
Penicillin G.......	300	10,000	5,000
Streptomycin-dihydro........	400	10,000	200
Fradicidin*.......	20,000	100,000	5,000,000
Neomycin*.......	1,000	200,000	1,000
Tyrothricin†......	5,000	100,000	1,000,000
Chloromycetin....	65	150	100,000
Thiolutin§.......	...	850	100,000
Bacitracin§.......	...	4,000	10,000
Polymyxin§......	...	3,500	200,000
Rimocydin§......	...	5,000	30,000
Penicillin and streptomycin...	2	5	75
Fradicidin and neomycin......	3,000	100,000	2,000
Aureomycin and terramycin.....	100,000	1,000,000	2,000,000
Terramycin and penicillin.......	10,000	100,000	5,000,000
Chloromycetin and neomycin..	...	0	0
Chloromycetin, penicillin and streptomycin...	...	0	0

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* Obtained through the courtesy of Commercial Solvents Corp., Terre Haute, Indiana.

† Obtained through the courtesy of Sharp & Dohme, Glenolden, Pa.

§ Obtained through the courtesy of Chas. Pfizer and Co., New York, N. Y.

TABLE III

PLATE COUNT ESTIMATES OF NUMBERS OF BACTERIA PER ML. OF ANTIBIOTIC-TREATED SEA WATER AFTER DIFFERENT PERIODS OF TIME

The sea water was collected from Oslofjord, Norway

Antibiotics, 50 ppm	Number of viable bacteria per ml.		
	12 hours	24 hours	72 hours
None (control)	5,000,000	2,000,000	800,000
Aureomycin	55,000	320,000	1,100,000
Terramycin	85,000	10,000	2,900,000
Penicillin	2,700	900	43,000
Streptomycin	10,000	62,000	110,000
Fradicidin	23,000	2,000,000	3,300,000
Neomycin	45,000	33,000	170,000
Tyrothricin	...	2,750,000	1,800,000
Chloromycetin	2,700	16,000	2,000
Thiolutin	63,000	850,000	1,100,000
Bacitracin	33,000	3,000,000	1,300,000
Polymyxin	60,000	1,100,000	1,600,000
Rimocydin	620,000	2,250,000	1,800,000
Ilotycin	2,800	1,000	13,000
Penicillin and streptomycin	25	6	325
Penicillin and chloromycetin	150	40	15
Aureomycin and chloromycetin	400	90	40
Penicillin, streptomycin and neomycin	80	33	450
Penicillin, streptomycin and polymyxin	700	70	270
Penicillin, neomycin and polymyxin	250	175	200
Aureomycin and polymyxin	3,250	2,000	50,000
Penicillin and polymyxin	500	150	200
Terramycin and polymyxin	6,000	8,000	50,000

distilled water. The samples were plated using nutrient sea water agar medium No. 2216 (ZoBell, 1946).

The pelagic eggs of the Pacific sardine (*Sardinops caerulea*), the Norwegian codfish (*Gadus callarias*), and a turbot (*Pleuronichthys* sp., probably *ritteri*[3]) were investigated. The very fragile sardine eggs, which average 1.8 mm. in diameter, were collected from the ocean near the Scripps Institution by a one-meert plankton net (0.18 mesh). The eggs of the turbot were smaller and more spherical. The fresh plankton samples in sea water were transported to the laboratory in two-quart jars. Fertile eggs were separated from the rest of the plankton; the time interval from the collection of the eggs to their separation was usually from one to three hours. Because of their rapid development, only the early stages or young eggs were selected for the experiments. Normally the sardine eggs are spawned at night from the hours of eight PM to midnight (Ahlstrom, 1948); when collected the following morning, they were at a sufficiently early stage for the experiments. Both types of eggs matured to the larval stages in from three to four days, depending on the water temperature.

The codfish eggs were obtained from ripe, mature adults which were caught in Oslofjord. The eggs were stripped into a flat pan filled with sea water and fertilized by the addition of fresh sperm. The eggs and sperm were mixed and allowed to stand for 10 minutes after which time they were washed with sea water and placed in a cylinder to separate the fertilized eggs which floated to the top. The codfish eggs were spherical, 1.5 mm. in diameter, and developed to larvae in approximately 16 days at 5°C.

The eggs (Table IV) were washed in sterile sea water and transferred to sterile glass containers where they were allowed to incubate either in antibiotic solution or in running sea water. For each experiment with fish eggs, sea water for both the antibiotic solution and running sea water was obtained from the same source, either collected directly from the ocean or from laboratory sea water systems. Thus any toxicity from the water source or pipe systems was equally active against the eggs cultivated, whether in the antibiotic solutions or in running sea water. The antibiotic solutions were recirculated or allowed to flow into the flask at a rate approximately the same as that of the running sea water. The glass containers were placed in a constant temperature water bath set to maintain the temperature of the water where the eggs were collected. Cod eggs were also hatched in cotton-stoppered flasks containing 100 ml. of sea water and various single antibiotics (Table V). Twenty eggs were tested in each flask. The sea water was not changed

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[3] This flatfish was identified by Dr. Grace L. Orton, Scripps Institution of Oceanography.

TABLE IV

PERCENTAGE OF EGGS OF *Sardinops*, *Pleuronichthys* AND *Gadus* THAT HATCHED, AND NUMBER OF BACTERIA BY PLATE COUNTS, IN RUNNING SEA WATER AND IN SEA WATER TREATED WITH 50 PPM EACH OF PENICILLIN AND STREPTOMYCIN

Genus	Number of eggs tested	Running sea water		Sea water plus antibiotics	
		% hatched	Bact./ml.	% hatched	Bact./ml.
Sardinops...	50	0	12,000	80	0
Sardinops...	50	10	...*	86	...*
Sardinops...	50	8	1,000	100	40
Pleuronichthys...	50	13	5,000	80	0
Gadus.......	100	1	30,000	28	1,100
Gadus†.....	100	65	25,000	78	1,500

* Not determined.
† Plus polymyxin.

TABLE V

PERCENTAGE OF TWENTY EGGS OF *Gadus* FROM OSLOFJORD, NORWAY, THAT HATCHED IN SEA WATER TREATED WITH 50 PPM EACH OF VARIOUS ANTIBIOTICS AT 9°C.

Antibiotics	Percentage of eggs hatched
None (control)	65
Penicillin and streptomycin	80
Penicillin and polymyxin	80
Streptomycin and chloromycetin	0
Aureomycin and polymyxin	95
Terramycin and polymyxin	0
Penicillin, streptomycin and neomycin	85
Penicillin, streptomycin and polymyxin	85

during the incubation and the eggs hatched without being disturbed. At intervals during their incubation the numbers of hatched eggs were recorded and the numbers of viable bacteria were determined.

Experiments were also performed on board a research vessel in an area of maximum sardine spawning. The area was off San Cristóbal Bay, Baja California, approximately 29 miles offshore and about 400 miles south of San Diego, California. The sardine eggs were collected from a depth of 10 meters. Fifty early-stage eggs, separated under a microscope, were placed in 50-ml. vials containing sterile sea water. The open vials were covered by cheesecloth having ½-mm. mesh and placed in two jars. One jar was provided with running sea water at a temperature of 16°C. from the area near collection. The other jar contained a mixture of 50 ppm each of penicillin and streptomycin which was changed every 12 hours. Both jars were maintained at approximate constant temperature in a bath of running sea water. At the end of three days the contents of the vials were preserved in formalin for later examination at the shore laboratory. Upon termination of the cruise, the sardine eggs in the vials were examined by phase microscopy and the numbers of hatched and unhatched eggs were counted. Microscopic examinations were made on wet preparations by Spencer phase contrast using a 97-×, dark-M objective.

RESULTS

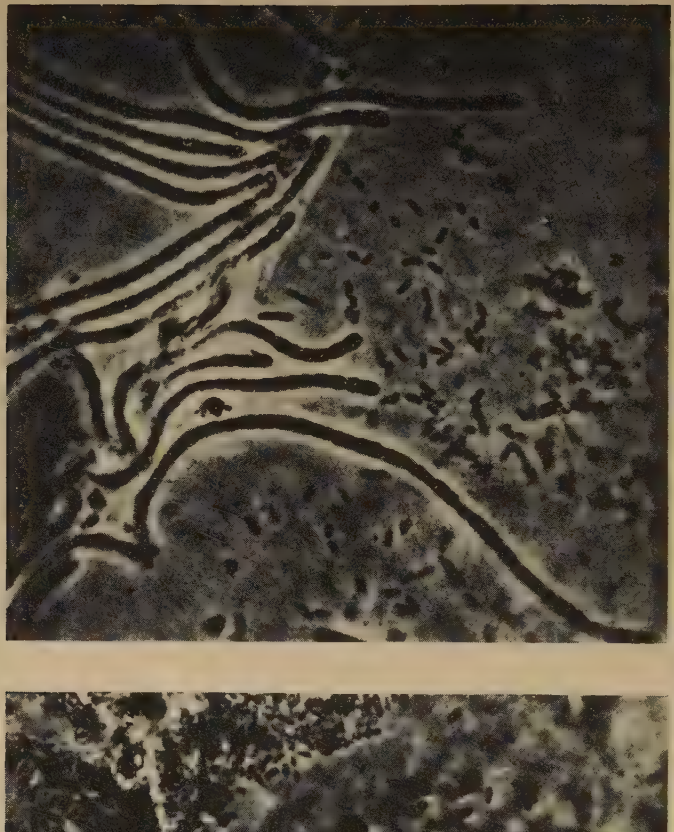
The most effective concentration of antibiotics proved to be 50 ppm, as indicated by a representative selection of several data (Table I). Above this concentration most of the antibiotics were somewhat toxic, and at lower concentrations the antibiotics showed decreased bacteriostatic activity. Therefore 50 ppm was used in subsequent experiments.

In the southern California region, combinations of penicillin-streptomycin and of chloromycetin-neomycin were the most effective in reducing the bacterial populations (Table II), but differed in toxicity for fish eggs. Marine fish eggs placed in a fresh solution of penicillin-streptomycin evidenced no ill effects, but the chloromycetin-neomycin mixture injured the eggs.

Toxicity tests for cod eggs indicate that 50 ppm of chloromycetin, aureomycin-neomycin, terramycin-polymyxin and tyrothricin were lethal after 12 hours of incubation.

In the area of Oslofjord, Norway, several combinations of antibiotics were more or less effective. In no instances were the bacteria completely eliminated by the use of antibiotics, and it was not unusual to have one or two species remaining (Table III).

Tables IV and V show several experiments which compare the hatching of the various eggs in sea water with and without antibiotics. As is shown, a higher rate of hatching occurred in the antibiotic-treated sea water except for the certain antibiotic mixtures which were



Phase micrographs showing microorganisms on the surface of living codfish eggs. × 2,000.

toxic. Many of the eggs in untreated sea water became opaque during the incubation, while those in antibiotic-treated sea water remained clear. Microscopic examinations (Plate I) revealed the abundance and types of bacteria that accumulated on the surface of the eggs during incubation in running sea water. The eggs of the cod, which needed a longer hatching time, were covered first with bacteria and then with various types of diatoms and dinoflagellates. These eggs usually became so heavy with attached organisms that they sank to the bottom of the flask. In most of these experiments the eggs in running sea water had many bacteria on their surfaces, while the eggs in antibiotic solution had relatively few bacteria.

DISCUSSION

Marine conditions are somewhat different from those of terrestrial environments where antibiotics are commonly employed. For example, certain of the antibiotics such as terramycin and aureomycin may be less bacteriostatic in sea water, which contains approximately 3.4 percent salts. Furthermore, aureomycin, which is most active at a pH of 7.0, is not so effective in sea water at pH 8.2.

The normal bacterial flora of sea water is variably affected by different antibiotics. However the inhibitory properties of the antibiotics may depend on the source of water with respect to temperature, organic material, salinity etc. Certain antibiotics inhibited marine bacteria (Tables II and III). Some had no effect, while others appeared to stimulate bacterial reproduction (Table II; compare the control with aureomycin HCl). The stimulatory effect was not studied further, so it is problematical whether the antibiotics provided a growth-promoting substance or merely suppressed one or more groups of bacteria allowing better growing conditions for those remaining. Of all the antibiotics examined, penicillin, streptomycin and chloromycetin appeared to be the most effective in reducing bacterial populations. Mixtures of these compounds reduced the populations in water near La Jolla to a point where no microbial growth was detected in nutrient sea water medium.

The mixture of terramycin and penicillin gave interesting results. Although the compounds when used separately reduced the bacterial population, the mixture had less effect. These results suggest that the two antibiotics were antagonistic to each other in combinations. This counter effect has been noted by Speck, Jawetz and Gunnison (1951), who reported that aureomycin interfered with the action of penicillin both *in vitro* and *in vivo* when species of *Streptococcus* and *Klebsiella* were the test organisms.

At a concentration of 50 ppm, chloromycetin, neomycin, polymyxin and rimocydin killed small fish and dinoflagellates within 12 hours. The combination of penicillin and streptomycin had little or no toxicity over long-range experiments with fish eggs, larvae or adults. In the botanical laboratory at Scripps Institution, Beatrice M. Sweeney (in 1952; personal communication) determined that the combination of penicillin and streptomycin at 50 ppm each is nontoxic to *Gymnodinium splendens* and produces bacteria-free cultures of this dinoflagellate. Its reproduction, however, is prevented. After the organisms were replaced in an antibiotic-free medium, reproduction and growth were more rapid than normal. Hoffman (1949) successfully eliminated freshwater bacteria by the use of the combination of penicillin and streptomycin in the isolation of pure cultures of *Saprolegnia* and *Aschlya.*

It is possible that bacteria have much more influence on the eggs of marine organisms than has been realized. Although *in situ* conditions are very difficult to duplicate in the laboratory, the evidence on hand suggests that bacteria accumulate on the eggs until present in sufficient numbers to be injurious. It is not known whether the large numbers of bacteria on the egg surfaces is due to the attraction by surface charge or by reproduction of the bacteria originally present. Both factors probably operate. Dannevig (1919) noticed that cod eggs became overgrown with organisms resembling *Leptothrix* which resembled the larger chain-like forms in Plate I. The phase photomicrographs (Pl. I) of the surface of a cod egg illustrate how concentrated the bacteria may become when the eggs are incubated in running sea water. The large chain-like organisms are an unknown species. Eggs incubated in an antibiotic solution of penicillin-streptomycin had few or no bacteria on the surface. In an experiment conducted to correlate the numbers of bacteria in the ocean with the presence of bacteria on the surface of the eggs collected in the same area, the surrounding water contained only a few bacteria per ml., and only an occasional egg had bacteria adsorbed on its surface.

Microscopic examinations showed that other organisms grew on the cod eggs. At times these populations became so great that the eggs lost their buoyancy and sank. According to Dannevig (1919), cod eggs cultivated in sunlight lost their buoyancy. Although Dannevig did not explain this effect, heavier diatoms or other organisms may have grown much faster in sunlight and therefore, by this additional weight, overcame the buoyancy of the eggs. This suggests that, if eggs were spawned in a fjord where dissolved oxygen was present only in the surface layers, the eggs thus losing their buoyancy might drop below the oxygen layer and subsequently die.

Marine bacteria may be responsible for a large proportion of abnormal eggs found in routine collections in areas of maximum sardine spawning on the California Coast. Ahlstrom (1948) has shown that as many as 45 percent of the eggs from net hauls may be abnormal. The abnormality was usually indicated by a cloudy appearance somewhat similar to denaturation. Similar eggs collected in 1953 had numerous bacteria on their surfaces. Large numbers of bacteria could cause the denaturation. ZoBell (1946) found 65 percent of the described marine bacteria to be proteolytic. Sette (1943) stated that the mortality of early stages of marine fishes is outstanding, as evidenced from a comparison between the numbers of eggs and larvae collected in plankton surveys. Rollefsen (1932) has reported that cod eggs are easily damaged by mechanical injury. The earlier-stage eggs were found to be the most susceptible.

It is reasonable to say that up to the present there has been found no comprehensive analysis of the term "natural mortality" in the population equations which have been prepared for natural stocks. The term has, in fact, been chiefly an item introduced by deduction into an arithmetic operation. Much attention has been paid to the measurement of the amount of mortality, but little work has been done on its cause, and that which has been done has been related chiefly to physical effects on the egg and larval stages. Thus Dannevig (1940) suggested that certain physical effects caused by high winds might be lethal to eggs; and Sette (1943) and others have written of the effects of currents in carrying eggs and larvae into situations unfavorable in respect to salinity, temperature or food supply.

The antibiotic solution did not increase the rate of egg development. The most significant point is that more than 75 percent of the eggs in antibiotic solution hatched. This discovery may prove significant in fish practice and it may also lead the way to the more successful rearing of the young stages of marine fishes.

SUMMARY

A series of thirteen antibiotics were tested alone and in combination for their effect on bacterial populations in sea water from the coast of southern California and from Oslofjord, Norway. Most of the aerobic, heterotrophic bacteria from sea water near La Jolla, California, were inhibited. While the antibiotics did appreciably decrease the numbers of bacteria in sea water from Oslofjord, more bacteria were resistant. Penicillin, streptomycin and chloromycetin were the most effective in reducing the bacteria populations; however, chloromycetin proved to be toxic to the eggs studied.

The pelagic eggs of the Pacific sardine (*Sardinops caerulea*), of the Norwegian codfish (*Gadus callarias*) and of a Pacific turbot (*Pleuronichthys* sp., probably *ritteri*) were investigated. The eggs were obtained by collection from the sea in plankton nets or by the removal and fertilization of mature eggs. The early-stage eggs were incubated in running sea water and in circulating sea water containing antibiotics. A mixture of penicillin and streptomycin did not appreciably increase or decrease the rate of development, but did increase the percentage of eggs hatching. This percentage in the antibiotic solution was three times greater than that in running sea water. Microscopic examinations demonstrated that the eggs in running sea water had many bacteria on their surfaces, while those in antibiotic solution had very few bacteria. Numerous bacteria were also demonstrated on the surfaces of later-stage eggs collected from the sea. During the long incubation time required by the cod eggs at 5°C., it was noted that an abundance of algae, bacteria

and diatoms were present on the egg shells. At this time the eggs lost their buoyancy and fell to the bottom of the incubation chamber.

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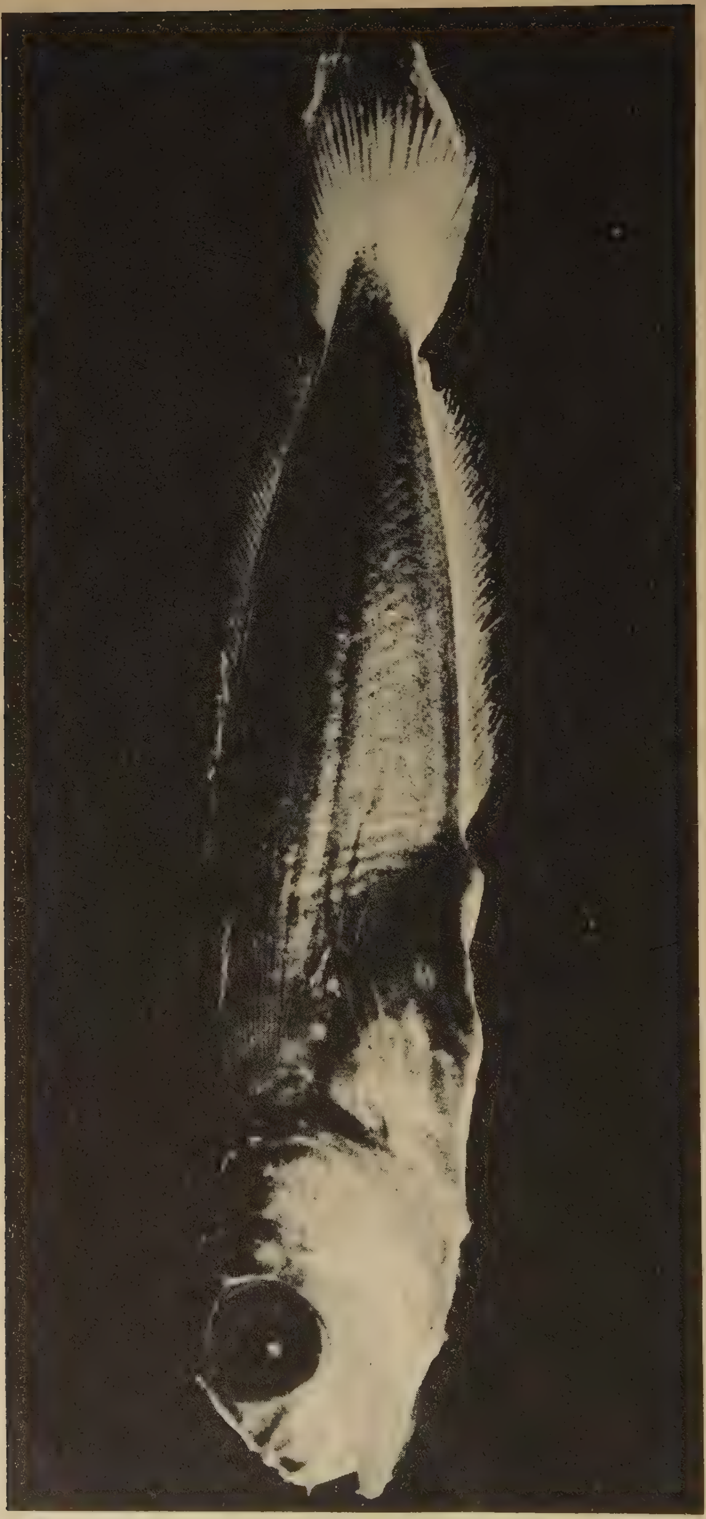

PHOTO BY SCRIPPS INSTITUTION OF OCEANOGRAPHY

"*Gaidropsarus vulgaris* (Yarrell)"—a juvenile from Laborador Sea. Standard length 23 mm.

A Juvenile Gadid Fish from the Ladrador Sea Representing a Species of *Gaidropsarus* Apparently New for North America[1]

CARL L. HUBBS

RECOGNIZING the impossibility of the occurrence in the Labrador Sea of any such tropical blenny, I requested the loan for study of the specimen reported as "*?Entomacrodus* sp." from Station "B" in the Labrador Sea, at Lat. 56° 30′ N., Long. 51° 00′ W. (Kielhorn, 1952: 246–7). The identification was speculative, for the recorder stated: "Except for its larger size, this fish resembles in many particulars one of the species of *Entomacrodus* as figured by Garman (1899, Plate L, Figure 1). Inasmuch as this is not a planktonic form, further taxonomic evaluation is being withheld until a later date." Charles J. and Marie Poland Fish, of the Department of Zoology, University of Rhode Island, promptly acceded to the request. An examination of the specimen showed at once that any resemblance to a blenniid is superficial.

The specimen (Pl. I), 23 mm. in standard length, obviously represents the juvenile stage of a species of the gadid genus *Gaidropsarus* (commonly called *Onos*), which is best developed in north-boreal waters (Svetovidov, 1948: 77–88), but has an antitropical distribution (Hubbs, 1952). It has a rudimentary barbel on the flap of each anterior nostril and one at the tip of the chin, but none at the front of the snout. The dorsal fin comprises an isolated ray (very short in this juvenile) at the nape, well separated except for a slight dermal fold from the otherwise undivided dorsal, which, like the undivided anal, is separated very narrowly from the rudimentary rays of the isocercal caudal.

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[1] Contributions from the Scripps Institution of Oceanography, New Series, No. 733.

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The slightly oblique base of the rounded pectoral fin lies in the upper half of the shoulder region. The pelvic fin, which has 3 upper rays isolated and produced, and has a strongly oblique base, arises immediately behind the shoulder girdle, well above the ventral edge of the breast and distinctly in advance of the pectoral base. The streamlined contours, compressed body, smoothly rounded head, and the strong silvery tone retained in formalin, even underlying the dark areas, stamp this fish as a pelagic juvenile of the type that has been developed independently by many unrelated fishes (Hubbs, 1941: 184–5). It has long been known that the gadids of this genus and of immediately related genera pass through such a pelagic stage, during which they are known in Britain as "mackerel midges."

The head and body are heavily charged with dark pigment and become almost sooty black in a diffuse band from the eye to the posterior part of the base of the main dorsal fin. The sides are also considerably darkened, deeply so toward a rather abruptly lighter area on the triangular caudal base. The belly is bright silvery, with fewer, weaker, and more scattered melanophores. The lower parts of the head are also light, except close to the eye and toward the outer edge of each mandible. The fins are whitish, except for dark linings on the produced pelvic rays. In life, no doubt, the upper parts are metallic blue; the lower parts, especially forward, bright silvery.

The ray formula (D approximately 65, A 51, P_1 24—24, P_2 8—8) fits only one species as currently recognized. This is the north-European species called *Onos vulgaris* (Yarrell) by Collett (1892: 12–3) and *Gaidropsarus vulgaris* (Yarrell) by Svetovidov (1948: 86–7), but referred by Collett (1903: 65–6) in a second paper to *G. argenteolus* (Montagu). The name *argenteolus* is now recognized as a synonym of *G. mediterraneus* (Linnaeus), and the name *vulgaris* appears to have been based on the same species (an opinion concurred in by N. B. Marshall of the British Museum). The north-European species with high ray counts has apparently never been validly named. I trust that some European ichthyologist with access to good material will soon supply a name. In the interim the name "*Gaidropsarus vulgaris* (Yarrell)" may be employed.

Two other species, the two that have been validly reported from Greenland (Jensen, 1948: 168–73), namely *G. ensis* (Reinhardt) and *G. argentatus* (Reinhardt), the latter commonly named *G. reinhardti* (Collett), also have 8 pelvic rays and more than 20 pectoral rays, but neither has more than 60 rays in the principal dorsal fin or as many as 50 in the anal. Jensen indicated that the pelagic young of *Gaidropsarus* appear commonly along the coast of Greenland, but he identified those he had as *G. argentatus*.

According to William V. Kielhorn (*in litt.*) the identification of this specimen with a European species "does not disagree with other data from the collection, namely, isolated specimens of *Sagitta setosa*, *Halocypris globosa?*, and *Physophora hydrostatica*, which appeared presumably from the eastward." Templeman and Fleming (1954) have just reported the European ling, *Molva molva* (Linnaeus), from Newfoundland. These recent discoveries of European species in America may be related to the Arctic amelioration of climate.

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Status of the Wood Ibis in San Diego County, California.—During the summer months in 1948, and from 1950 to 1953 (no observations were made in 1949), the Wood Ibis (*Mycteria americana*) was noted in some coastal sloughs and estuaries of San Diego County. The number of individuals frequenting the area in 1953 showed a marked increase over those seen in the previous years listed or indicated by published records. In the San Dieguito River mouth eight were seen on several occasions in July, 1948; a few were present in 1950 and 1951; sixteen occupied the area during the summer of 1952; on July 24, 1953, in contrast, seventy-eight were observed at dusk in flight from San Elijo Lagoon, at Cardiff-by-the-Sea, to an area about two miles east of Del Mar, in the San Dieguito River drainage. What appeared to be the same birds were repeatedly observed during July, August and September feeding by day on the flats and in the shallow waters of San Elijo Lagoon and retiring at night to the San Dieguito River area. While feeding they frequently churned the mud by vigorous stomping. Flights of the Wood Ibis over Solano Beach were seen daily at sundown and were also heard during the early hours of darkness as the birds continued to move to the resting area. Communication between the birds during night flight was often maintained by a continued chorus of hoarse croaks each answered by a high-pitched peep. The progression of flight during darkness was accomplished by circular soaring with gradual movement in the desired direction. Daylight flights were ordinarily more direct, although the soaring was observed on one occasion. In the absence of moonlight, observations of night flights were often possible by city light reflected from low overcast.

A flock of approximately 300 Wood Ibises was noted during July and August, 1953, just south of Oceanside in the Buena Vista Lagoon, which is being vigorously supported as a bird sanctuary. Local observers stated that this was the first occurrence of Wood Ibis on this lagoon since 1948. A few stragglers were also noted in Sorrento Slough and in Mission Bay. Over the Sorrento Slough six birds were observed soaring to a height of approximately 2000 feet only to climax the affair by plummeting to about 200 feet from the ground. The birds did not repeat this but settled down in shallow water.

This large migratory influx of Wood Ibis in 1953, presumably from the west coast of Mexico, is heartening to ornithologists who have watched with much anxiety the encroachment of commercial, recreational and flood control development in the slough, lagoon and shallow bay areas of southern California during recent years. As the available feeding grounds face severe reduction due to such development, we may be on the eve of seeing fewer, instead of more, of these American storks.—ANDREAS B. RECHNITZER, *Scripps Institution of Oceanography, University of California, La Jolla, California, March 17, 1954.*

Contribution from Scripps Institution of Oceanography, new series no. 734.

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Deep-Sea Research, 1954, Vol. 2, pp. 68 to 70. Pergamon Press Ltd., London.

Thermosteric anomaly and the analysis of serial oceanographic data

R. B. MONTGOMERY and WARREN S. WOOSTER

Summary—The pressure terms in the anomaly of specific volume of sea water are found to be negligible for hydrostatic computation in such regions as the upper layers of the equatorial Pacific Ocean. It is proposed that the anomaly of specific volume with pressure terms omitted be called *thermosteric anomaly*. This quantity is recommended for routine use in the tabulation and analysis of serial data. The systematic analysis of a vertical section can include hydrostatic computation by either of two graphical methods, one being WERENSKIOLD's method.

PRESSURE TERMS IN ANOMALY OF SPECIFIC VOLUME

THE common hydrostatic computation in oceanography is accomplished, following BJERKNES (1910), by numerical evaluation of an integral along a vertical line,

$$(\phi_2 - \phi_1)_a = \int_{p_2}^{p_1} \delta \, dp, \tag{1}$$

where $(\phi_2 - \phi_1)_a$ is the anomaly of geopotential difference between the pressure p_1 at the greater depth and the pressure p_2 at the lesser depth. The specific volume α has been separated into two terms,

$$\alpha = \alpha_{35,0,p} + \delta,$$

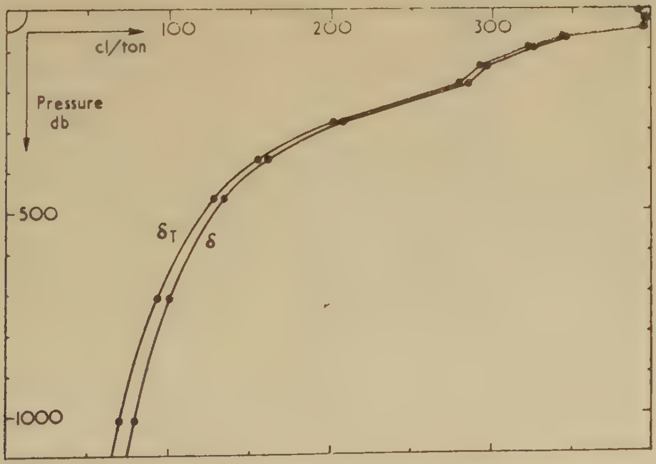

Fig. 1. Comparison of specific-volume anomaly δ and thermosteric anomaly δ_T at *Carnegie* station 148, 19 October 1929, 24°57′N, 137°44′W.

where $\alpha_{35,0,p}$, the specific volume of sea water of salinity 35 per mille at 0 C, is a function of pressure alone and δ is the anomaly of specific volume (*steric anomaly* would be shorter). The anomaly of specific volume is itself separated into six terms,

$$\delta = \delta_s + \delta_t + \delta_{st} + \delta_{sp} + \delta_{tp} + \delta_{stp},$$

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Table 1. *Anomaly of geopotential difference at* Carnegie *stations, in kilergs per gram (or centimetres)*

Station	*Latitude*	*Longitude*	$\int \delta \, dp$		$\int (\delta - \delta_T) \, dp$		*Remarks*
			0 db *to* 500 db	500 db *to* 1,000 db	0 db *to* 500 db	500 db *to* 1000 db	
14	42°10′N	47°19′W	69·3	26·7	2·75	3·93	Meridional section in central North Atlantic
15	38°39′N	48°48′W	92·1	68·9	4·33	10·08	
16	36°47′N	46°31′W	94·5	46·5	3·94	6·92	
18	29°47′N	40°36′W	91·3	52·7	4·08	8·37	
19	24°00′N	39°36′W	97·3	48·7	4·12	7·74	
20	19°13′N	38°28′W	97·7	46·3	3·83	6·46	
21	15°50′N	37°56′W	82·3	42·7	3·03	5·43	
22	13°25′N	38°00′W	81·7	45·3	2·86	5·48	
23	10°50′N	37°24′W	79·8	44·2	2·71	5·02	
24	8°15′N	36°10′W	80·9	44·1	2·42	4·71	
107	14°05′N	146°06′E	165·6	50·4	3·17	4·46	Western North Pacific
108	18°26′N	144°01′E	171·7	61·3	3·68	4·92	
109	23°22′N	144°08′E	139·1	64·9	3·31	4·46	
110	26°20′N	144°24′E	133·6	68·4	3·52	4·72	
111	31°00′N	144°16′E	124·0	59·0	3·10	3·92	
112	33°51′N	141°15′E	143·3	67·7	3·58	4·98	
113	34°44′N	141°04′E	142·9	53·1	3·19	3·75	
114	36°38′N	143°34′E	86·4	46·6	2·02	2·92	
115	37°40′N	145°26′E	100·7	49·3	2·09	2·81	
116	38°41′N	147°41′E	71·5	42·5	1·24	2·70	
117	40°20′N	150°58′E	75·9	45·1	1·37	2·83	
118	42°29′N	155°24′E	69·3	44·7	1·08	2·68	
119	45°24′N	159°36′E	59·8	38·2	0·79	2·23	
120	47°02′N	166°20′E	59·7	39·3	0·80	2·26	
130	37°05′N	123°43′W	82·5	48·5	1·77	3·66	Section from California to Hawaii
131	33°49′N	126°20′W	105·2	48·8	1·95	3·48	
132	31°38′N	128°48′W	107·8	50·2	2·00	3·56	
133	29°21′N	132°30′W	116·2	51·8	2·37	3·56	
134	27°45′N	135°22′W	118·8	50·2	2·44	3·74	
135	26°39′N	139°07′W	118·2	50·8	2·44	3·60	
136	26°13′N	142°02′W	117·5	51·5	2·55	3·60	
137	24°02′N	145°33′W	131·0	51·0	2·74	3·90	
138	22°53′N	151°15′W	146·6	53·4	3·01	3·90	
139	21°47′N	155°31′W	132·4	50·6	2·65	3·86	
140	23°26′N	159°27′W	155·4	54·6	3·13	3·81	
148	24°57′N	137°44′W	123·4	50·6	2·57	3·76	Section in equatorial Pacific
149	21°18′N	138°36′W	124·2	52·8	2·60	4·16	
150	16°15′N	137°06′W	111·3	48·7	2·54	4·40	
151	12°40′N	137°32′W	90·6	50·4	2·55	4·74	
152	10°05′N	139°44′W	83·4	50·6	2·51	4·94	
153	7°45′N	141°24′W	119·2	49·8	2·66	4·77	
154	6°42′N	143°22′W	127·0	50·0	2·70	4·80	
155	4°51′N	146°46′W	135·6	49·4	2·86	4·86	
156	3°01′N	149°46′W	138·0	49·0	2·96	4·68	
157	1°48′S	152°22′W	124·4	48·6	3·06	4·64	
158	6°33′S	154°58′W	134·0	49·0	3·11	4·78	
159	9°24′S	159°01′W	142·6	48·4	3·30	4·54	

each depending on salinity, temperature, and pressure to the extent indicated by the subscripts. The last three terms are referred to as the *pressure terms*. The sum of the first three terms is determined by salinity and temperature and is here designated δ_T (SVERDRUP, 1933, uses the symbol $\Delta_{s,T}$), so

$$\delta = \delta_T + \delta_{sp} + \delta_{tp} + \delta_{stp}.$$

It is proposed that the quantity δ_T, heretofore nameless, be called *thermosteric anomaly*. Defined physically, thermosteric anomaly is the anomaly of specific volume (steric anomaly) that would be attained if the water were changed isothermally to a standard pressure of one atmosphere. The distributions of thermosteric anomaly and specific-volume anomaly at a typical station are shown in Fig. 1.

It seems always to have been taken for granted that the pressure terms in the anomaly of specific volume are important. To see whether the pressure terms may be neglected for certain purposes, the *Carnegie* stations listed in Table 1 are examined, the data being taken from FLEMING *et al.* (1945). The stations were selected to illustrate a variety of situations as noted in the table.

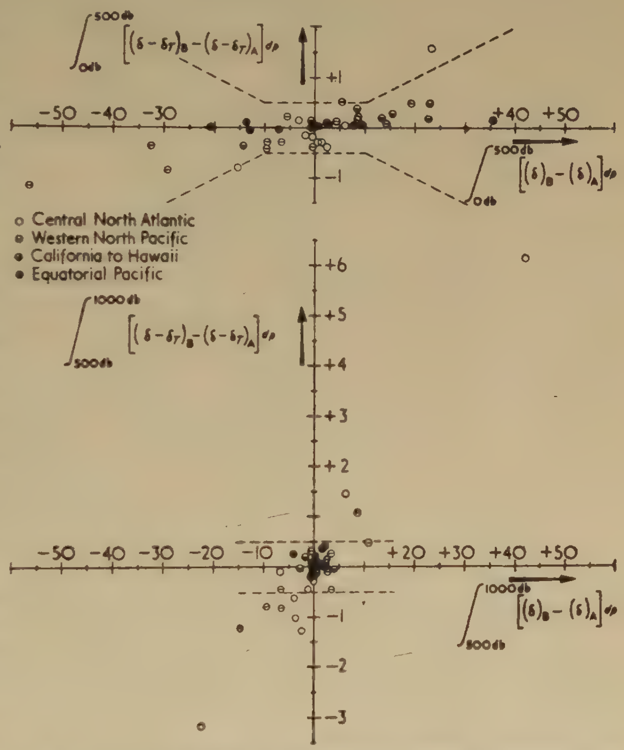

Fig. 2. Station-to-station change in thickness of the layer 0 db to 500 db (above) and of the layer 500 db to 1,000 db (below). The part of the change contributed by the pressure terms is shown as ordinate in comparison with the total change shown as abscissa. The ordinate scale is exaggerated ten times. The units are kilergs per gram (or centimetres). Data from Table 1.

The anomaly of geopotential difference (1) is tabulated for each station for the layers from 0 db to 500 db and from 500 db to 1,000 db. For the same pressure intervals, Table 1 also shows the integral of the pressure terms,

$$\int_{p_2}^{p_1} (\delta_{sp} + \delta_{tp} + \delta_{stp})\, dp = \int_{p_2}^{p_1} (\delta - \delta_T)\, dp. \qquad (2)$$

The terms δ_{sp} and δ_{tp} were read from LAFOND's (1951) Tables VI and VII. The term δ_{stp} was found from the Hydrographic Tables of BJERKNES (1910) to be insignificant.

For the station values in Table 1, the differences between successive stations are shown in Fig. 2. It is seen that in the upper layer the station-to-station change of the integrated pressure terms (ordinate) is always small: with the exception of one Atlantic station, this change is either less than 0·5 cm or less than 5 per cent (sloping dashed lines) of the total change of layer thickness (abscissa). In the deeper layer the change of the integrated pressure terms is as large as 6 cm for one pair of Atlantic stations, but for all station pairs on the section from California to Hawaii and on the section in the equatorial Pacific the change is less than 0·5 cm.

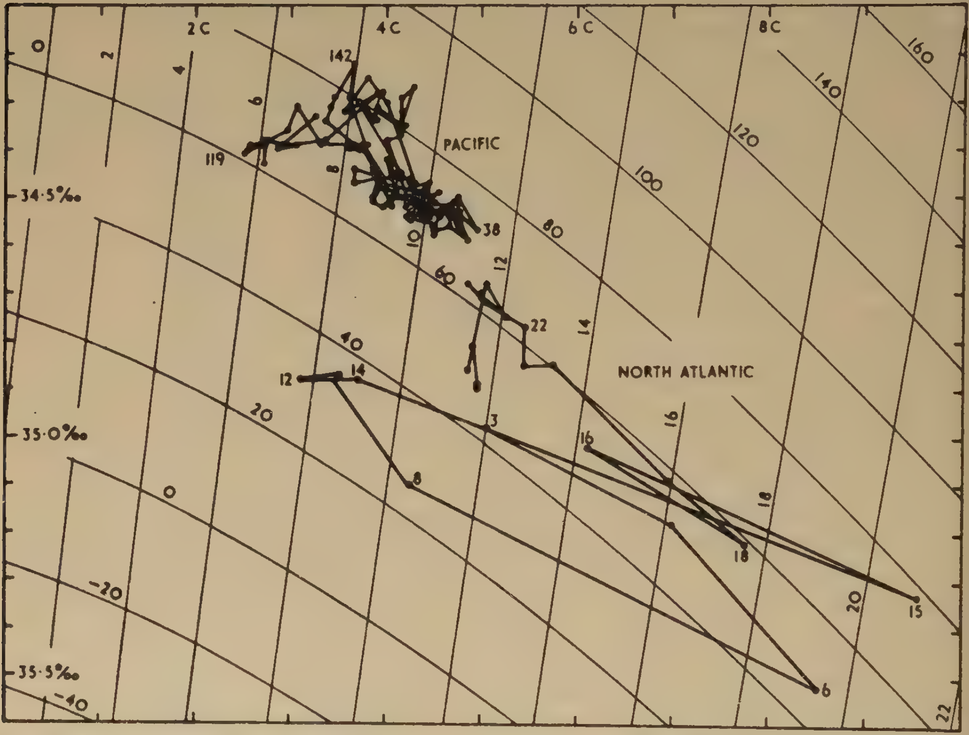

Fig. 3. Temperature-salinity diagram for 1,000 db. All *Carnegie* stations reaching 1,000 db are represented by the dots consecutively connected; some are labelled with station numbers. The diagonal curves represent thermosteric anomaly. The nearly vertical lines represent the pressure terms of specific-volume anomaly at 1,000 db. Both families are labelled in centilitres per ton.

Another way of assessing the pressure terms is by study of Fig. 3, a temperature-salinity diagram for 1,000 db at 154 *Carnegie* stations. Thermosteric anomaly and the pressure terms are shown by the two families of lines. For the Pacific stations the range in pressure terms is seen to be only 6 cl/ton (centilitres per ton), which for a 500-db layer amounts to 3 cm in thickness, and the change between adjacent stations is at most about 1 cl/ton. The Atlantic stations cover a greater area on the diagram, which thus reflects greater baroclinity at 1,000 db in the Atlantic than the Pacific.

The conclusion is reached that for hydrostatic computation limited to the upper 500 db or 1,000 db, especially in the Pacific Ocean, if extreme precision is not required and if significant convenience is gained, the pressure terms may be neglected; in other words, the thermosteric anomaly δ_T may be used in place of the complete specific-volume anomaly δ.

THERMOSTERIC ANOMALY RECOMMENDED

Oceanographers have fallen into the cumbersome habit of using both density and specific volume, the first as sigma-*t* and the second as anomaly of specific volume.* It would be better in all routine work to adhere to one or the other. The question is which to choose.

Sigma-*t* (σ_t) is defined as the excess above one gram per millilitre that the density would attain if the water were changed isothermally to a standard pressure of one atmosphere. Density ρ and specific volume bear the relation $\alpha\rho = 1$. Hence, thermosteric anomaly and sigma-*t* bear the relation

$$(\alpha_{35,0,0} + \delta_T)(1\ \mathrm{g\,ml^{-1}} + \sigma_t) = 1, \qquad \alpha_{35,0,0} = 0{\cdot}972643\ \mathrm{ml/g}$$

Sigma-*t* is commonly used as a quasi-conservative or identifying property of water type. For any such purpose, including isentropic analysis, the use of thermosteric anomaly is equally suitable. Sigma-*t* has the advantage that it has become established in habit. Thermosteric anomaly has the convenience that it is expressed, for most ocean water, in a number of two or three digits only, whereas the corresponding number in sigma-*t* has four digits.

The use to which specific-volume anomaly is commonly put is in hydrostatic computation by the method indicated in equation (1). Hydrostatic computation can also be carried out by integrating the density anomaly ϵ,

$$(p_1 - p_2)_a = \int_{\phi_1}^{\phi_2} \epsilon\, d\phi. \tag{3}$$

Both methods are discussed by BJERKNES (1910). There are some reasons to prefer the method of equation (1). One reason is that this method has become customary. This method gives the geopotential difference between chosen isobaric surfaces. The geostrophic equation for isobaric surfaces is the simplest because it does not involve density, which appears in the geostrophic equation for a level surface. For this reason, isobaric surfaces have been adopted in meteorology as the basis for upper-air analysis. Furthermore, if pressure is directly observed, the integration in (1) involves observed quantities and yields geopotential difference as a result. If depth rather than pressure is observed, the integration (1) is more convenient than (3), because the number of metres of depth equals the number of decibars of pressure within one per cent in the upper layers, whereas the number of metres of depth differs from the number of 10^5 ergs per gram of geopotential difference by about two per cent.

The conclusion is reached that it would be better in all routine work to adhere to specific volume. It is desirable, therefore, to replace the use of sigma-*t* with the use of thermosteric anomaly. The most important specific-volume quantity to tabulate with serial observations, in our opinion, is thermosteric anomaly. If specific-volume anomaly is to be tabulated along with thermosteric anomaly, the computation will be easier than has been the computation of both sigma-*t* and specific-volume anomaly.

Convenient tables exist for the calculation of thermosteric anomaly. Besides the Hydrographic Tables of BJERKNES (1910), there is the convenient new Table V of LAFOND (1951) for the salinity range from 21 to 37 per mille and temperature range from − 2 C to 30 C.

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* Another such habit is the use of both salinity and chlorinity.

Another method is to read thermosteric anomaly from a temperature-salinity diagram bearing the isopleths, as in Fig. 3. Furthermore, the pressure terms, and hence the complete anomaly of specific volume, can be obtained from such a temperature-salinity diagram. This method is feasible because the pressure terms are nearly linear with pressure. (As may be seen from the tables of BJERKNES or SVERDRUP, the relation is linear, for practical purposes, from 0 db to 2,000 db or deeper.) It is convenient to have the pressure terms for 1,000 db drawn on the diagram, as in Fig. 3, so that the value from the diagram needs merely to be multiplied with the ratio of the pressure to 1,000 db.

ANALYSIS OF SECTIONS

A recent paper by one of us (MONTGOMERY, 1954) describes a unified method of analyzing a section of serial observations, the aim being to achieve consistency in the description of the different fields (temperature, salinity, sigma-*t*, oxygen . . .). Sigma-*t* was chosen as the reference field. As concluded above, it now appears desirable to replace sigma-*t* with thermosteric anomaly.

In the paper mentioned, no attempt was made to incorporate hydrostatic computation into the analysis and to represent the geostrophic flow through the section. The field of thermosteric anomaly that results from this analysis is based on a systematic study of all pertinent data and is more reliable than a simple interpolation of water-bottle data for each station independently. This field should therefore form the basis for hydrostatic computation along the section.

By adding the pressure terms, the field of thermosteric anomaly can be converted to the field of specific-volume anomaly. It has been seen, however, that the pressure terms are unimportant for some problems. For these problems the field of thermosteric anomaly may be used directly in the hydrostatic equation (1) in place of specific-volume anomaly.

For isopleths of either specific-volume anomaly or thermosteric anomaly the word *isanostere* is proposed.

The starting point is the vertical section showing isanosteres on coordinates of horizontal distance (x) and pressure (p). There are two ways to proceed with the hydrostatic computation. The first method is to compute the anomaly of geopotential difference between chosen isobaric surfaces by summing the pressures of isanosteres at each chosen vertical line. The second, introduced by WERENSKIOLD (1935, 1937), is to compute the relative slope of chosen isobaric surfaces by summing the slopes of isanosteres at each chosen vertical. The first is more direct if the position of the sea surface relative to a chosen isobaric surface is desired; the second is more direct if the slope of an isobaric surface is desired for use in the geostrophic equation. The two methods are discussed in turn. Note that in either of these graphical methods the computation can be made for any verticals, which need not coincide with stations.

For the first method, the variable of integration in (1) is changed from pressure to anomaly of specific volume,

$$(\phi_2 - \phi_1)_a = p_1\,\delta_1 - p_2\,\delta_2 + \int_{\delta_1}^{\delta_2} p\,d\delta. \qquad (4$$

If the isanosteres are drawn for a uniform, small increment $\Delta\delta$, the integral in (4 can be evaluated for any vertical on the section by summing the pressures of th isanosteres directly from the section and multiplying by the increment $\Delta\delta$.

For WERENSKIOLD's method, the integral in (1) is differentiated with respect to x, the distance along the section,

$$\frac{d}{dx}\int_{p_1}^{p_2}\delta\,dp=\int_{p_1}^{p_2}\left(\frac{d\delta}{dx}\right)_p dp=\int_{\delta_1}^{\delta_2}\left(\frac{d\delta}{dx}\right)_p\left(\frac{dp}{d\delta}\right)_x d\delta=-\int_{\delta_1}^{\delta_2}\left(\frac{dp}{dx}\right)_\delta d\delta,$$

the last step being a consequence of the relation between three variables

$$\left(\frac{d\delta}{dx}\right)_p\left(\frac{dx}{dp}\right)_\delta\left(\frac{dp}{d\delta}\right)_x=-1.$$

Hence,

$$\frac{d}{dx}(\phi_2-\phi_1)_a=\int_{\delta_1}^{\delta_2}\left(\frac{dp}{dx}\right)_\delta d\delta. \tag{5}$$

(This result could be obtained by differentiating (4)). If the isanosteres are drawn for a uniform, small increment $\Delta\delta$, the integral in (5) can be evaluated for any vertical by summing the slopes of the isanosteres and multiplying with the increment $\Delta\delta$.

Let v_n be the geostrophic-current component normal to the section, positive v_n being directed contra solem from positive x. The geostrophic equation is

$$f(v_{n2}-v_{n1})=d\,(\phi_2-\phi_1)_a/dx,$$

where $f=2\omega\sin\phi$ is the Coriolis parameter, ω being the angular speed of the earth's rotation and ϕ being latitude. The quantity on the right results directly from (5) or indirectly from (4).

In conclusion, the method of analysis previously described should be modified by replacing sigma-t with thermosteric anomaly. The field of thermosteric anomaly can be converted to the field of specific-volume anomaly by adding the pressure terms, but the method is most convenient when the pressure terms may be neglected completely. As part of the analysis, hydrostatic computation can be carried out graphically by one of the methods just described.

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On the sounding of trenches

ROBERT L. FISHER

Summary—During 1952-53 the Scripps Institution of Oceanography research vessels *Horizon* and *Spencer F. Baird* made extensive bathymetric investigations of the Tonga and Japan Trenches. The greatest minimum travel-time recorded from the Tonga Trench corresponds to a depth of 5,814 ± 15 fathoms (10,633 ± 27 metres), corrected. If this value were accepted as the true depth, it would be the deepest sounding yet recorded from the Southern Hemisphere, but careful study of the records indicates that the actual maximum depth in this area is probably at least 5,900 fathoms. This measurement was made by recording the echoes from the explosion of a small charge with a hydrophone and pen oscillograph. The principal sources of error in this method are evaluated; errors in interpretation of such sonic soundings are probably many times as great as the errors in measurement. Soundings in the Japan Trench were recorded with a high-frequency echo-sounder. Results of this investigation in the Ramapo Deep indicate a maximum depth of about 5,250 fathoms (9,600 metres), corrected.

PART 1

Exploration of the Tonga Trench by *R/V Horizon*

A. INTRODUCTION

IN DETERMINING and in discussing the configuration of the sea-floor it is necessary to distinguish rather carefully between the terms " sounding " and " depth." A sounding, at a point at sea, is an interpreted measurement expressed as a depth and appears as a depth notation on nautical charts. The depth at such a point, however, is the vertical distance from the sea surface to the bottom and its magnitude is in no way dependent on sounding measurements.

In attempting to determine depth various measurements are made; for example, travel-time in sonic sounding, length in wire sounding, or temperature and/or pressure. In sonic-souding, the travel-time is multiplied by the velocity of sound in sea water and the product is expressed as a length. The echo-sounder generally incorporates this step in its recording system; the travel-time is multiplied by a constant nominal value for sound velocity and the recorder scale is read in terms of length. The echo-sounder may detect all bottom echoes from within its beam pattern; the first arrival, which is usually accepted as the sounding, is merely the reflection from the nearest part of the sea-floor. When the bottom is nearly horizontal and of small relief there is little error introduced by taking the first arrival in computing the depth; if the bottom is irregular this error may be very great. The following discussion attempts to show how an analysis of the entire echo train may permit a truer estimate of depth in regions of moderate to large bottom relief.

B. DESCRIPTION OF METHOD AND DISCUSSION OF SOUNDINGS

In December, 1952, and January, 1953, during the Scripps Institution of Oceanography CAPRICORN Expedition, the research vessels *Horizon* and *Spencer F. Baird* made 24 lines of soundings across the Tonga Trench, between latitudes 14°30′S and 26°15′S. The greatest depths (FISHER and REVELLE, 1954) were found about 180

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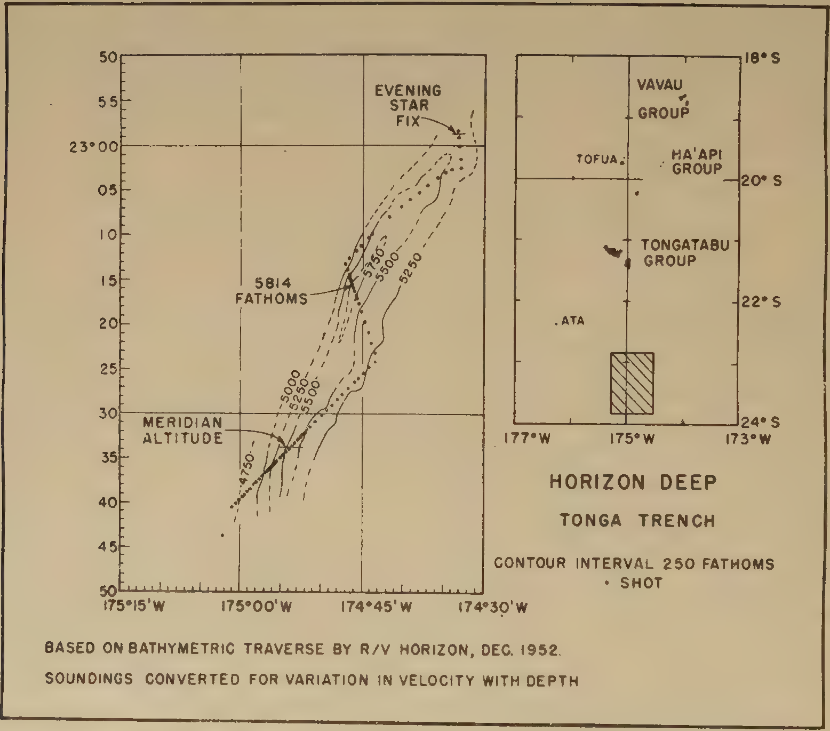
miles south of Tongatabu, the largest island of the Tongan Archipelago (Fig. 1, inset). It may be significant that the greatest depths recorded during this fairly detailed bathymetric exploration of the Tonga Trench lie very near the only abrupt change in trend of the trench axis, from N 25°E to about north-south at 24°15′S.

Nineteen of the crossings were made by *Horizon*, which was equipped with a high-frequency EDO echo-sounder modified to permit shoal scale operation on all ranges so that the instrument could be read to 10 fathoms even at great depths. Water noise, however, prevented the consistent recordings of depths greater than 4,000 fathoms; in such deep areas soundings were logged from audible returns. In all deep areas a standard NMC-2 echo-sounder was employed to give a supplementary record; the two fathometers gave comparable depth readings in all cases.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VAVAU GROUP
TOFUA
HA'API GROUP
TONGATABU GROUP
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18° S
20° S
22° S
24° S
177°W
175°W
173°W
HORIZON DEEP
TONGA TRENCH
CONTOUR INTERVAL 250 FATHOMS
• SHOT

BASED ON BATHYMETRIC TRAVERSE BY R/V HORIZON, DEC. 1952.

SOUNDINGS CONVERTED FOR VARIATION IN VELOCITY WITH DEPTH

Fig. 1. Topography of the *Horizon* Deep, based on shot-echo intervals expressed as equivalent depths.

The deepest portion of the Tonga Trench explored by *Horizon* was sounded by recording the echoes from explosions set off at shallow depths. As the ship proceeded at about 7·5 knots, half-pound demolition blocks with 14-inch fuses were dropped overboard at 3 to 10 minute intervals. The charge detonated at a depth of 10 to 12 fathoms; the firing-mark and echo-train were received on the echo-sounder hydrophone and recorded on one channel of a pen oscillograph. Timing marks were placed on the record at one-second intervals by means of a break-circuit chronograph. Sounding velocities, based on temperature measurements and salinities of water samples collected by *Baird* 200 miles north of *Horizon*'s position, were computed from tables compiled by KUWAHARA (1939). Samples were collected to 7,000 metre (3,800 fathoms) depth along the trench axis, and the computed velocity curve extrapolated to 5,000-6,000 fathom depths. The positions of the deep soundings were determined by dead reckoning between morning and evening star fixes, supplemented by a latitude from meridian altitude at noon.

Fig. 1 is a contoured plot based on the observed travel times of first arrivals as determined by the explosion-oscillograph method, expressed as equivalent depths. This plot has not been corrected for slope-echo effects; in preparing the chart each computed depth was plotted at the ship's position corresponding to the time the measurement was made. As in several other trenches, notably the Acapulco and Aleutian Trenches, the nearshore wall (in the Tonga Trench the western wall) is generally steeper than the offshore wall.

The deepest sounding shown on Fig. 1, 5,814 fathoms ± 15 fathoms, lies at latitude 23°15·5′S, longitude 174°46·5′W, with a possible error in position of two miles. In accordance with recent practice in deep-sea floor nomenclature (WISEMAN and OVEY, 1953, p. 14), it is here suggested that this sounding be called the Horizon Depth, after the exploration vessel. WÜST recently (1950-51, p. 213, and 1952, p. 114) has reviewed the greatest depths yet reached by echo and wire soundings. From his compilation the Horizon Depth, Tonga Trench, exceeds the Galathea Depth, Mindanao Trench, by about 50 fathoms and ranks second to the Challenger Depth, Marianas Trench, among the deep areas discovered to date. As has been pointed out by FISHER and REVELLE (1954) and as will be demonstrated in detail in the following section, the maximum depth traversed by *Horizon* was probably at least 5,900 fathoms.

C. EVALUATION OF SOUNDING ERRORS IN THE EXPLOSION-OSCILLOGRAPH METHOD

The explosion-oscillograph method outlined above eliminates sounding errors arising from frequency fluctuations or mechanical errors in the echo-sounder. However, the soundings obtained are subject to several errors of reading, timing and interpretation, so that a critical evaluation of the magnitude of such errors is required.

(1) *Reading and correcting the oscillograph records*

At the oscillograph paper speed employed (about 2·5 cm/sec) the shot record can be marked and read to an accuracy of better than 0·01 second. The shot-echo interval is the sum of two such measurements, plus a long intermediate period bounded by time marks, the total being rounded off to the nearest hundredth of a second. Since a time interval of 0·01 second corresponds to a depth difference of 4·2 fathoms, an error of less than 10 fathoms in the sounding may be introduced.

Since the charge explodes at shallow depth several hundred feet behind the ship, the firing-mark recorded at the ship is late and the shot-echo interval recorded is several hundredths of a second too short. A correction factor, constant so long as the ship's speed, the firing time and the shot depth remain constant, must be added to the interval as recorded. In *Horizon*'s investigation this correction was computed in the following manner:

if D = the horizontal distance the ship moves after dropping the charge and prior to the shot,
d = depth at which the charge detonates,
c = mean sound velocity between the surface and the charge depth,
T_r = travel time recorded,
T_{s-s} = travel time, surface to surface,

then

$$T_{s-s} = T_r + \frac{d}{c} + \frac{\sqrt{D^2 + d^2}}{c}$$

With a shot depth, d, of about 65 feet, a horizontal displacement, D, of 435 feet (35 seconds at 7·5 knots), and a mean sound velocity between the surface and depth of shot of 5,030 feet/second (based on bathythermograph measurements), the correction factor to be added to the recorded shot-echo interval is 0·10 (0) second.

(2) *Variation in the timing mark*

Error due to daily gain or loss in the chronometer is negligible. The magnitude of the error in the oscillograph circuit is not known, but total error in timing is almost certainly less than 0·01 second.

(3) *Errors in the sounding velocities applied*

Since the sounding velocities used in computing water depth from recorded travel times were based on hydrographic data from a very deep cast in a comparable environment only 200 miles distant, these velocities as applied are probably accurate to one part in a thousand, in this case corresponding to an uncertainty in depth of 5 or 6 fathoms. About 3/4 of the travelled path lies in water which is nearly isothermal and isohaline. Under such conditions sound velocity variation is almost entirely a function of pressure, so that extrapolating the sounding velocity curve 2,000 fathoms beyond the deepest temperature-salinity observations introduces no significant error.

(4) *Travel path error*

A negligible error is introduced by assuming that the depth, or vertical path, is one-half the travelled path. If the water depth is 34,500 feet (5,750 fathoms) and the horizontal distance from shot position to the ship's position when receiving the echo is 435 feet, then one-half the travelled path $= \sqrt{(34{,}500)^2 + \left(\frac{435}{2}\right)^2} = 34{,}500$ $(1{\cdot}00002) \approx 34{,}500$ feet.

(5) *Recognition of significant returns*

In the interpretation of the shot records two very important assumptions are :

(*a*) the marked return is a bottom echo, not spurious noise, and
(*b*) the bottom echo from directly beneath the ship, if a first arrival, did not go unmarked.

Plate 1, a reproduction of 13 consecutive shot records from the profile yielding the deepest soundings, furnishes clear evidence on assumption (*a*). On all of these

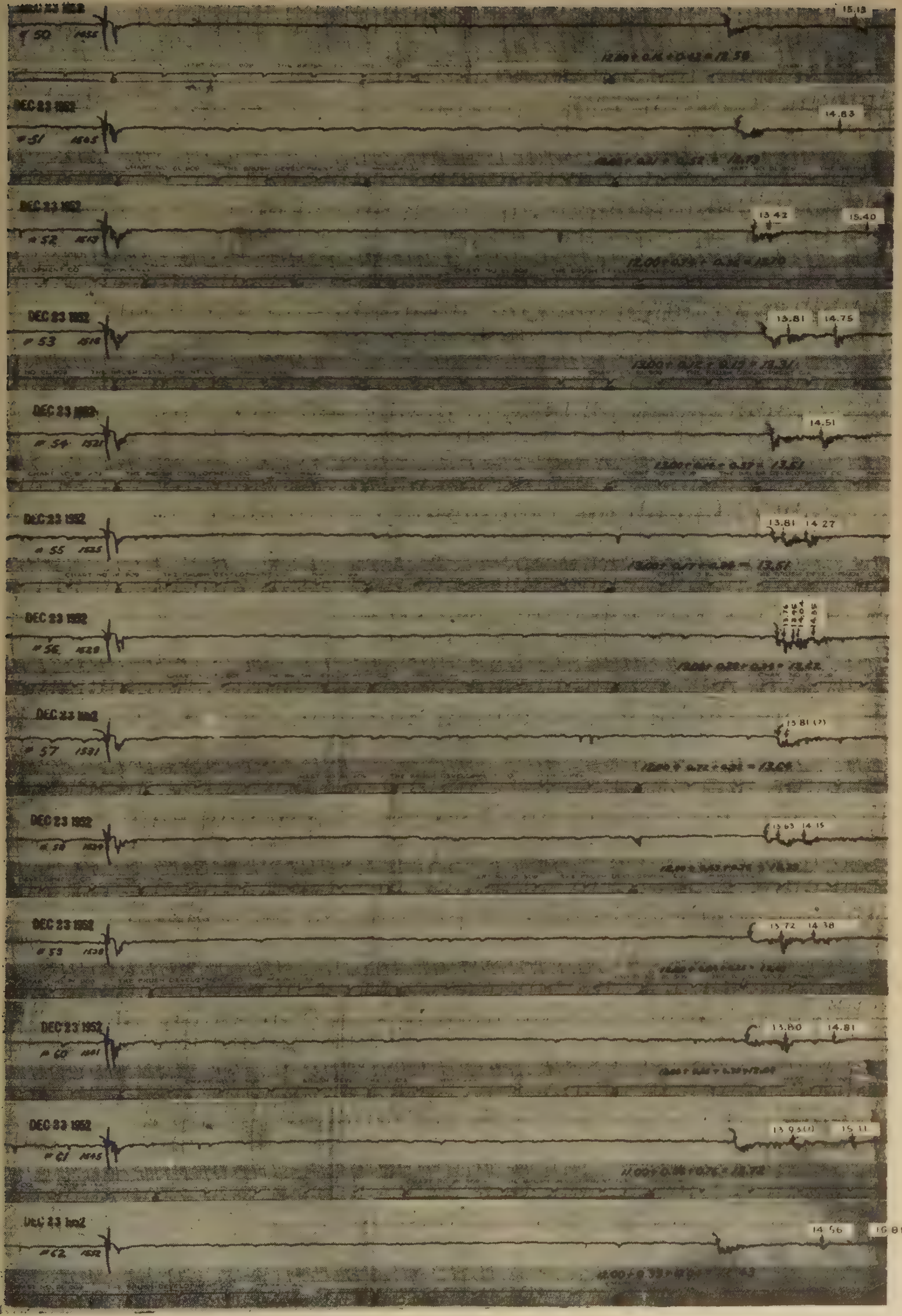

Plate 1. Oscillograph records 50-62, from the shot-profile yielding the deepest Tonga Trench sounding

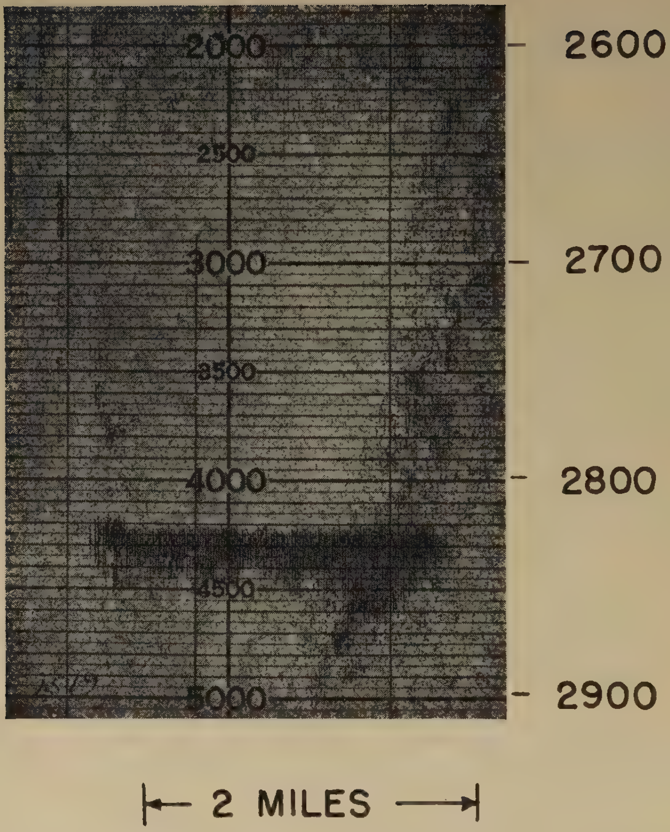

PLATE 2. Portion of fathogram from the Acapulco Trench. Strong echo from flat bottom at 2,820 fathoms.

shot records the disturbances marked as echoes are much longer and stronger than any of the short duration pulses occurring randomly along the records. The marked returns show a consistent increase in shot-echo interval to shot number 57 and then a decrease to shot 62; there are no stray returns. On each record the minimum echo time has been taken for computing the sounding; on several records (notably 53 and 59) a stronger later pulse is recorded.

With regard to assumption (*b*), the author and his colleagues have often observed that a rather flat depression, such as a trench bottom partly filled by sediments, generally gives a stronger return on the echo-sounder than would a steep, rough and possibly rocky slope such as a trench flank. HESS and BUELL (1950, p. 403), in a detailed discussion of sounding data from the Mindanao Trench and the Ramapo Deep, reached the opposite conclusion and maintain that the stray, especially deep soundings logged by the *Emden* and *Ramapo* were actually echoes from neighbouring slopes farther from the ship than was the true bottom.* The writer agrees fully that such inconsistent deep soundings are probably side echoes and that the echo from directly beneath the ship came back earlier and was missed. However, the more characteristic relative strength of echoes from a trench bottom and a trench slope is shown in Plate 2, a portion of a fathogram recorded in the Acapulco Trench. Here the very weak echoes from the trench walls migrated downward through the strong echo from the nearly flat trench bottom. No fathogram of comparable quality is available for the Tonga Trench, but the same relationship between echo strengths has been observed in the Tonga, Aleutian, Kurile-Japan and Acapulco Trenches and in the Cedros deep on recent Scripps Institution expeditions. Furthermore, echo sounding results from the recent investigations of the Marianas Trench by H.M.S. *Challenger* support this interpretation. According to GASKELL, SWALLOW and RITCHIE (1953, p. 61),

> " The echo was sometimes lost for a few consecutive transmissions, but was always loud and clear at the deepest part of the trench. The weak echo may come from steep slopes, and soundings taken at one-minute intervals do sometimes show sudden changes of 50-70 fathoms after a flat bottom stretch of several minutes duration."

It is probable that the above relationship between the strength of side and bottom echoes from trenches holds for impulses from explosions as well as for the higher frequency fathometer pulses. Similar records were obtained on *Horizon* with an oscillograph used alternately to record reflections from explosions and fathometer ping reflections between shots. *Spencer F. Baird* recorded fathometer ping returns by oscillograph to obtain more accurate deep soundings than could be logged audibly, but the quality of such records is poorer than that of the records from explosions.

(6) *Slope echoes*

The possibility that some of the echoes marked on Plate 1 return from neighbouring shallower portions of the sea floor rather than from directly beneath the ship was examined by describing arcs, of radius equal to the indicated sounding, about the corresponding position of the ship. The effect of such echoes would be to mask true bottom and to make the trench appear narrower than its actual width. This sounding line runs at a large angle (about 48°) to the trend of the trench bottom, so that slope echoes are considered to come chiefly from ahead of or behind the ship rather than from either side. From this analysis it is probable that the first returns on shot records 51, 52, 53, 54, and 55 come from farther east, on the trench wall, than the ship's indicated position. First returns on records 58, 59 and 60 probably are reflections from the west wall of the trench. The evidence from such an analysis

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* However, in a personal communication, HESS agrees that as a rule echoes from the flat floor of a trench are usually stronger than from the walls.

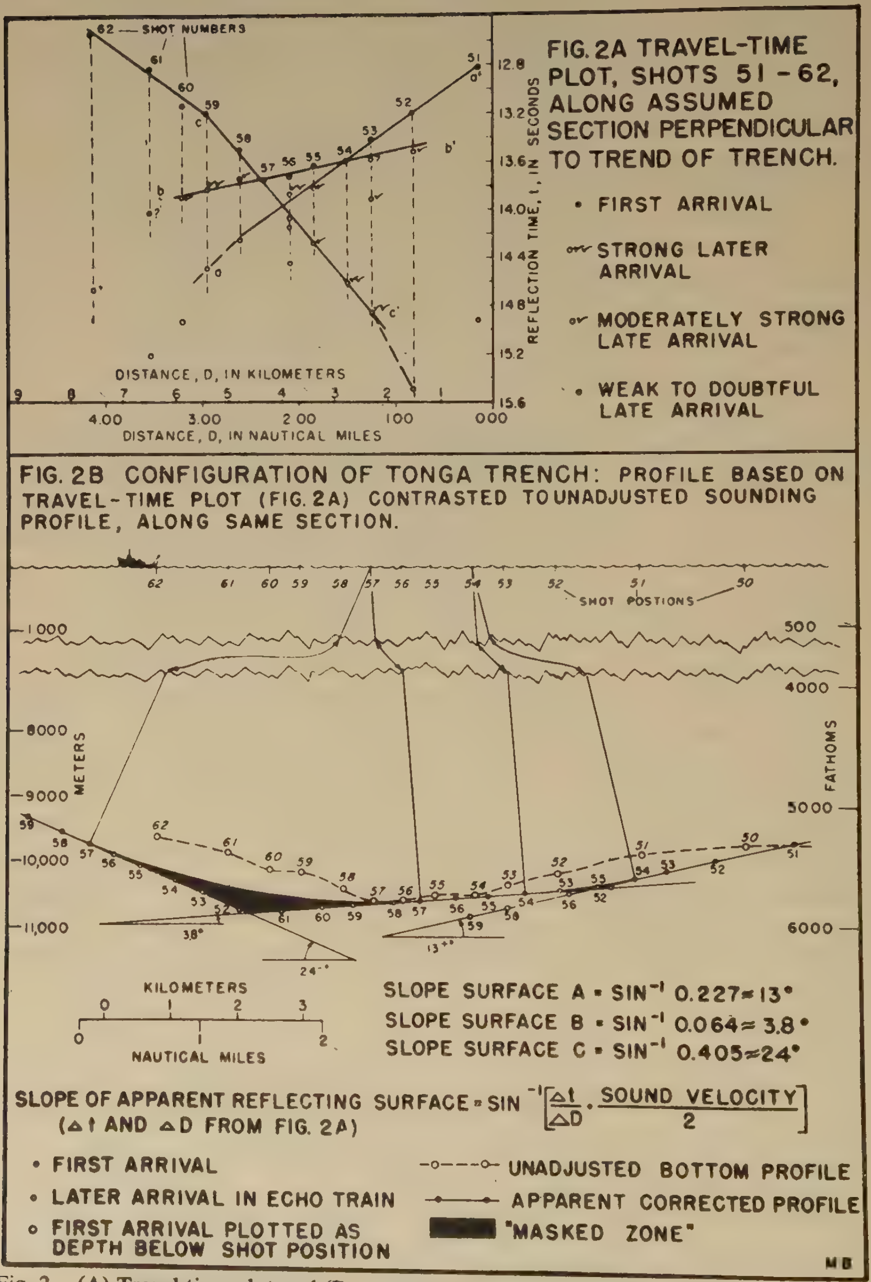

Fig. 2. (A) Travel-time plot and (B) topographic interpretation from shot records 51-62.

is inconclusive for the first return on record 57, corresponding to the 5,814 fathom sounding, and record 56. If these first arrivals too are slope echoes, as well they may be, the trench is deeper than 5,814 fathoms.

Much more rewarding, and possibly less misleading, is a detailed examination of the records of the echo trains themselves. Fig. 2a is a travel-time plot of all readable echoes from shots 50-62. In preparing this plot the shot positions along the ship's track were projected on a line normal to the trend of the trench as shown in Fig. 1, and the distance along the assumed section was measured from an arbitrary point just east of the position of shot 50. A line *a-a′* may be fitted, by the usual method of least squares, through the plotted first arrivals from records 51, 52, 53 and 54, and later arrivals on records 55, 56 and possibly 58 and 59. A similar line, *b-b′*, is fitted through first arrivals on records 54, 55, 56, 57 and possible later arrivals on 52, 53, 58, 59 and 60. A third line, *c-c′*, has been fitted through the first arrivals from records 57, 58 and 59, and good later arrivals on records 53, 54, 55 and 56. The echoes joined by a line such as *a-a′* are assumed to return from a single reflecting surface, parallel to the trend of the trench. If such a correlation is accepted, the dip of the apparent reflecting surface may be computed from the slope of the travel-time line and the sound velocity. From Fig. 2a it appears that three major reflecting surfaces may be proposed: two steep trench walls and a gently-dipping, westward-sloping trench bottom. In the case of shots 54 and 57, the first arrivals may return from two planes simultaneously, or possibly a second echo returns too soon after the first arrival to be resolved. This simplified interpretation neglects changes in trend as well as small irregularities on the trench walls; such departures from an ideal surface would be present, of course, and would help account for the scatter in the travel-time on any line. Variation in ship's speed may also introduce error into the travel-time plot.

In Fig. 2b the apparent reflecting surfaces are plotted as segments of a trench profile. Two lines were plotted tangent to a circle of radius equivalent to 5,814 × 6 feet, centred at shot position 57: one, representing the west wall, dips easterly at 24°; the other dips westerly at 3·8°. Similarly, a line dipping westerly at 13° was drawn tangent to a circle of radius equivalent to 5,755 × 6 feet, centred at shot position 54. The 3·8°-dipping line is also tangent to this second circle. Along each line the most probable points of reflection (for minimum reflection travel-time) for each shot have been determined by dropping a perpendicular to the line from the corresponding shot position. The probable point of reflection of the first echo arrival from each shot is shown by a solid circle, the possible reflection points of later arrivals from each shot are shown as open circles. An unadjusted bottom profile (dashed line in Fig. 2b) with first-arrival travel-time expressed as water depth plotted directly below the corresponding ship's position, has been projected along the same section, normal to the trend of the trench.

Several conclusions regarding the interpretation of echo-sounding results may be drawn from Fig. 2b. In constructing the trench profile, based on the travel-time plot of Fig. 2a, it has been assumed that the first arrival on record 57 is the sum of the reflections from the west wall and the gently-sloping bottom, arriving simultaneously, and the first arrival on record 54 comes from the trench bottom and the east wall simultaneously. The appearances of the first breaks in the echo trains of records 54 and 57 are suggestive in this connection; they are sharper and stronger than the first breaks on adjacent records. If such nearly-simultaneous arrivals are present, there is in each case a " masked " zone between the two reflection points. With a broad beam receiver, reflections from the bottom lying within the zone never could appear as first arrivals, though possibly, especially in the case of a basin partly filled by sediment, they would arrive as strong later reflections. Only by using a narrow-beam echo-sounder could the vertical distance to bottom within the " masked zone " be determined. An approximate maximum depth may be obtained by projecting to intersection the apparent reflecting planes. From the data as interpreted here the greatest depth along this profile is probably at least 5,900 fathoms (10,800 metres), vertically beneath a point between shot positions 60 and 61 at the intersection of the 24°-dipping and 3·8°-dipping planes. Again it must be emphasized that the reality of this depth, both as to magnitude and position, is chiefly dependent on the validity of the travel-time plot. Small changes in the values computed for the slopes make appreciable changes in this indicated depth. In view of the small number of observations included in the slope determinations no value for the probable error in this depth is proposed. Sedimentary fill would reduce the depth; a steepening of the trend walls downward, as is sometimes observed, would increase it. Neither of these conditions can be detected here.

The horizontal distance from the plotted position of the deepest sounding, directly below shot position 57, to the point on the assumed west wall giving the same reflection time is 2·8 miles. It is entirely possible, however, that this maximum sounding is based on a reflection from the bottom on either side of the ship's track.

From the profiles here developed the maximum difference in depth as computed from the travel-time-slope analysis and depth based on a single travel-time record plotted beneath the shot position is about 450 fathoms, at a point between shot positions 60 and 61. The difference between the two methods of interpretation is in this case about 30 times as great as the uncertainty in the measurement of the travel time.

D. CONCLUSIONS

The assessment of the errors involved in the explosion-oscillograph method of sounding has been developed in detail to permit setting limits of error to the deep soundings taken by *Horizon*. Aside from questions of interpretation, the greatest uncertainties lie in reading the oscillograph records and in the sounding velocities applied. Under the conditions of the *Horizon* soundings, a maximum error of 10 fathoms from the former and 5 fathoms from the latter seems reasonable, so that the longest travel time for a first echo from the Horizon Depth corresponds to 5,814 ± 15 fathoms. Such a degree of precision supports the conclusion reached by ADAMS in evaluating a nearly-identical method (ADAMS, 1942, p. 553):

> " The data are inconclusive but seem to indicate that sounding with bombs should give results within the specified accuracy of 99·5 per cent for depths of 3,000 fathoms or greater."

From the discussion of the interpretation of the sounding results, however, it is plain that this sounding is not a valid maximum for the region of the Horizon Deep; it is merely a minimum interpreted value for the reflection travel-time at one shot position. A better estimate is obtained by analysis of the echo trains of all shots along the profile. From this it is evident that the deepest point traversed by *Horizon* was probably at least 5,900 fathoms.

PART II

Exploration of the Ramapo Deep by the *Spencer F. Baird*

THE area of the Ramapo Depth (HESS and BUELL, 1950, p. 405) in the Japan Trench southeast of Honshu was visited by the Scripps Institution of Oceanography research vessel *Spencer F. Baird* during the 1953 Trans-Pacific Expedition. The primary

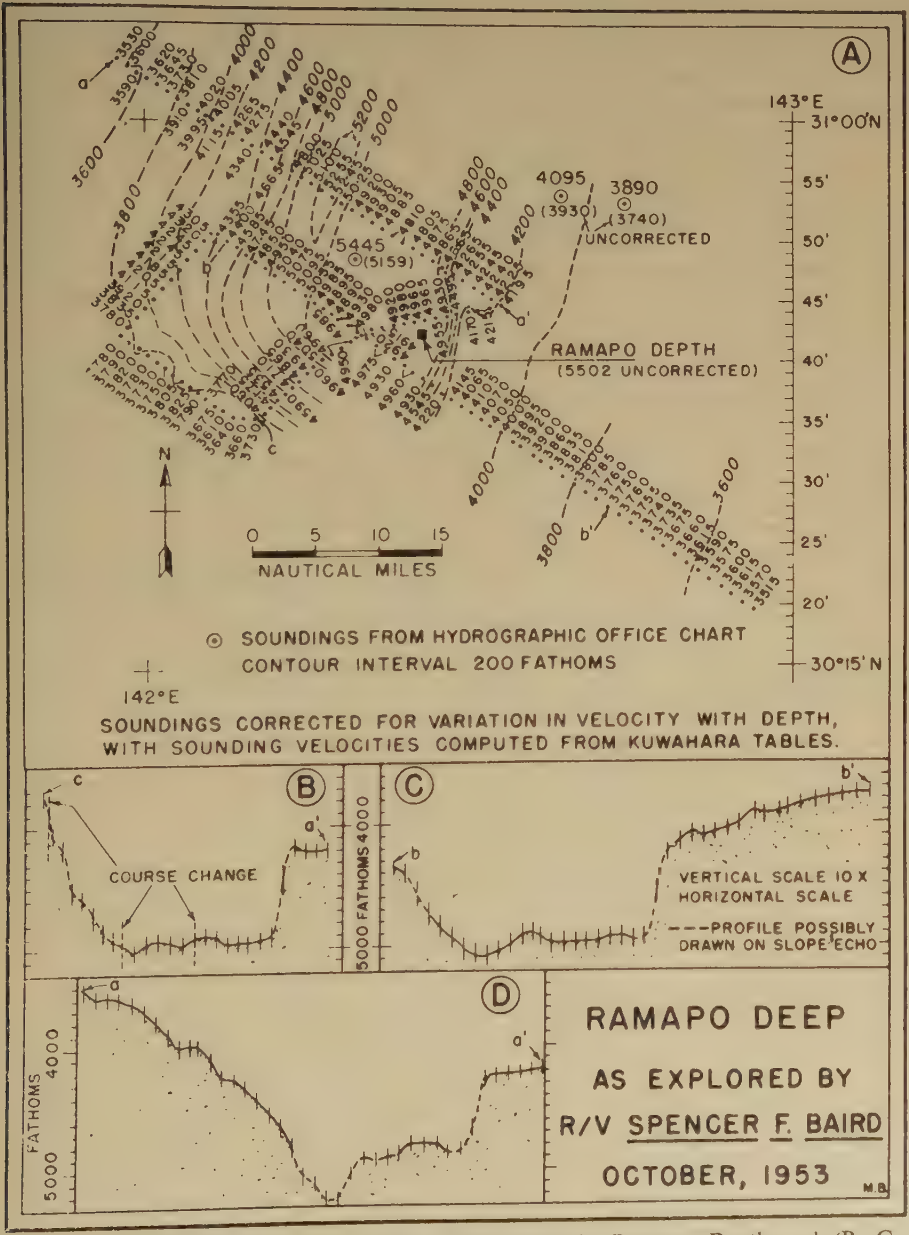
A
143°E
31°00'N
55'
50'
45'
40'
35'
30'
25'
20'
30°15'N
142°E
3600
3800
4000
4200
4400
4600
4800
5000
5200
4095
(3930)
3890
(3740)
UNCORRECTED
5445
(5159)
RAMAPO DEPTH
(5502 UNCORRECTED)
a
b
c
b'
N
0 5 10 15
NAUTICAL MILES
⊙ SOUNDINGS FROM HYDROGRAPHIC OFFICE CHART
CONTOUR INTERVAL 200 FATHOMS
SOUNDINGS CORRECTED FOR VARIATION IN VELOCITY WITH DEPTH, WITH SOUNDING VELOCITIES COMPUTED FROM KUWAHARA TABLES.
B
c
a'
COURSE CHANGE
5000 FATHOMS 4000
C
b
b'
VERTICAL SCALE 10 X HORIZONTAL SCALE
---PROFILE POSSIBLY DRAWN ON SLOPE ECHO
D
a
a'
FATHOMS
4000
5000
RAMAPO DEEP
AS EXPLORED BY
R/V SPENCER F. BAIRD
OCTOBER, 1953
M.B.

Fig. 3. (A) Sounding lines run by *Spencer F. Baird* near the Ramapo Depth and (B, C, D) unadjusted bottom profiles with soundings plotted as depths.

objectives of the expedition were hydrographic and biological investigations, but some time was available for examining the sea-floor topography in this area.

Like *Horizon*, *Spencer F. Baird* is equipped with a high-frequency EDO echo-sounder modified to allow shoal-scale stylus and recording speeds on all ranges. A detailed trace of the bottom topography was obtained at the greatest depths, although the echo was occasionally lost on steep slopes. The echo-sounder was operated continuously. Although several abrupt changes in level were noted, the soundings varied consistently; there were no single deep soundings flanked by much shallower readings. During the Ramapo Deep exploration the frequency of the current to the echo-sounder motor remained constant at 60·4 cycles per second; the soundings as read have been multiplied by 60·0/60·4 to correct for the deviation from standard frequency. Due to mechanical errors of the echo-sounder the readings recorded by stylus on the 4,200-4,800 and 4,800-5,400 fathom scales are 20 to 30 fathoms shoaler than the soundings obtained by recording on an oscillograph the ping and echo received by hydrophone. Therefore, 25 fathoms was added to the observed soundings to get corrected nominal (assumed sound velocity of 4,800 feet/second) soundings.

Positions of the soundings were obtained by LORAN and by back-tracking from radar and visual cuts on the small islands of the Nanpo Shoto 125 miles to the west. The maximum error in position is 6 miles; the probable error is 3 to 4 miles.

Nominal soundings were corrected by computation of sounding velocities from the Kuwahara tables. *Spencer F. Baird* made several 2,000-3,000 metre hydrographic casts in the southern Japan Trench and found practically no lateral variation in temperature and salinity at depths greater than 545 fathoms (1,000 metres). Therefore sounding velocities for the Ramapo Deep were computed from temperature and salinity measurements from a deep (3,440 fathom) cast 70 miles north in the trench.

Fig. 3a is a contoured plot of the corrected soundings from the *Spencer F. Baird* traverses only. The soundings were plotted at 5-minute intervals along the track, but intermediate one-minute soundings were considered in drawing the contours. An abrupt change in trend of the trench axis from north-northeast to nearly south-east, or an abrupt narrowing of the trench, can be postulated from the *Baird* soundings. A good crossing of two *Baird* lines was obtained at 4,955 fathoms. The Ramapo Depth, shown on old Hydrographic Office charts as 5,502 fathoms uncorrected, lies between two 4,700 fathom (uncorrected) *Baird* soundings and is, as HESS and BUELL (1950, p. 405) maintain, of very doubtful validity. In the region explored by *Spencer F. Baird* the deepest sounding shown on recently published U.S. Hydrographic Office charts, 5,159 fathoms (5,445 corrected), is 190 fathoms deeper than the deepest *Baird* sounding, 5,255 fathoms (9,611 metres, at 30°54-1/2′N, 142°16-1/2′E). The *Baird's* traverse furnishes no information as to the validity of this sounding.

Figs. 3b, 3c, 3d are sounding profiles based on *Spencer F. Baird* soundings only. All three show an abrupt break on the offshore side of the trench, from a general level of 4,000-4,200 fathoms down to a general level of 4,800-5,000 fathoms. The knolls on this deep surface may be peaks or ridges partly buried by sediments slumped from zones higher on the east flank. The deepest soundings on each profile occur near the steep west flank of the trench, in an elongate basin 200-300 fathoms deeper than the 4,800-5,000 fathoms plain noted above. Such a deep " inner gorge " was found also on several of the deepest Tonga Trench crossings, and may be characteristic of such very deep trenches. The deepest *Spencer F. Baird* soundings on profile *a-a′*, may be slope echo returns, with the trench bottom actually deeper than 5,245-5,255 fathoms. The echo-sounding record for this crossing is not of sufficient quality to permit resolution of the echoes and construction of the apparent reflecting surfaces, as was attempted from the shot records from the Tonga Trench in the preceding discussion.

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Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter

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(Received April 28, 1954)

A method is developed for interpreting the statistics of the sun's glitter on the sea surface in terms of the statistics of the slope distribution. The method consists of two principal phases: (1) of identifying, from geometric considerations, any point on the surface with the particular slope required for the reflection of the sun's rays toward the observer; and (2) of interpreting the average brightness of the sea surface in the vicinity of this point in terms of the frequency with which this particular slope occurs. The computation of the probability of large (and infrequent) slopes is limited by the disappearance of the glitter into a background consisting of (1) the sunlight scattered from particles beneath the sea surface, and (2) the skylight reflected by the sea surface.

The method has been applied to aerial photographs taken under carefully chosen conditions in the Hawaiian area. Winds were measured from a vessel at the time and place of the aerial photographs, and cover a range from 1 to 14 m sec^{-1}. The effect of surface slicks, laid by the vessel, are included in the study. A two-dimensional Gram-Charlier series is fitted to the data. As a first approximation the distribution is Gaussian and isotropic with respect to direction. The mean square slope (regardless of direction) increases linearly with the wind speed, reaching a value of (tan16°)^2 for a wind speed of 14 m sec^{-1}. The ratio of the up/downwind to the crosswind component of mean square slope varies from 1.0 to 1.9. There is some up/downwind skewness which increases with increasing wind speed. As a result the most probable slope at high winds is not zero but a few degrees, with the azimuth of ascent pointing downwind. The measured peakedness which is barely above the limit of observational error, is such as to make the probability of very large and very small slopes greater than Gaussian. The effect of oil slicks covering an area of one-quarter square mile is to reduce the mean square slopes by a factor of two or three, to eliminate skewness, but to leave peakedness unchanged.

1. INTRODUCTION

THE purpose of this study was to make quantitative measurements pertaining to the roughness of the sea surface; in particular, to learn something concerning the distribution of slope at various wind speeds. This distribution plays an important part in the reflection and refraction of acoustic and electromagnetic radiation, and in the complex problem of wind stress on the water surface.

Our method consists in photographing from a plane the sun's glitter pattern on the sea surface, and translating the statistics of the glitter into the statistics of the slope distribution. Winds were measured from a vessel at the time and place the photographs were taken. They ranged from 1 to 14 m sec^{-1}.

If the sea surface were absolutely calm, a single, mirror-like reflection of the sun would be seen at the *horizontal specular point*. In the usual case there are thousands of "dancing" highlights. At each highlight there must be a water facet, possibly quite small, which is so inclined as to reflect an incoming ray from the sun towards the observer. The farther the highlighted facet is from the horizontal specular point, the larger must be this inclination. The width of the glitter pattern is therefore an indication of the maximum slope of the sea surface.

Spooner[1] in a letter to Baron de Zach reports four measurements by this method in the Tyrrhenian Sea, all yielding maximum slopes of 25°. Hulbert[2] demonstrates by this method that the maximum slope in the North Atlantic increased from 15° at a 3-knot wind to 25° at an 18-knot wind. Shuleikin[3] took a long series of measurements of the width of the "road to happiness" over the Black Sea (a Russian synonym for the glitter pattern from the setting sun), and deduced that slopes up to 30° were not uncommon.

These measurements of maximum slope, so widely separated in space and time, are reasonably consistent. They do depend, however, on the manner in which the outer boundary of the glitter pattern is selected. This selection is apparently influenced by the brightness of the light source relative to the sky, and by the sensitivity of the eye. For otherwise the moon's glitter would not appear narrower than the sun's glitter under otherwise identical conditions. We have avoided this difficulty by computing the distribution of slopes from the measured variation of *brightness within the glitter pattern* (rather than computing maximum slopes from the outer boundaries). Our method gives more information—and requires much more work.

The two principal phases are (1) to identify, from geometric considerations, a point on the sea surface (as it appears on the photographs) with the particular slope required at this point for the reflection of sunlight into the camera, and (2) interpret the average brightness of the sea surface (or darkening of the negative) at this point in terms of the frequency with which this particular slope occurs. By choosing many such points we derive the frequency distribution of slopes.

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* Scripps Institution contribution No. 737. This work has been supported by the Geophysical Research Directorate of the Air Force Cambridge Research Center, AMC, under contract No. AF 19(122)-413.

[1] J. Spooner, Corresp. Astro. du Baron de Zach, 6 (1822).

[2] E. O. Hulbert, J. Opt. Soc. Am. 24, 35 (1934).

[3] V. V. Shuleikin, *Fizika Moria* (Physics of the Sea) (Izdatelstvo Akad. Nauk. U.S.S.R., Moscow, 1941).

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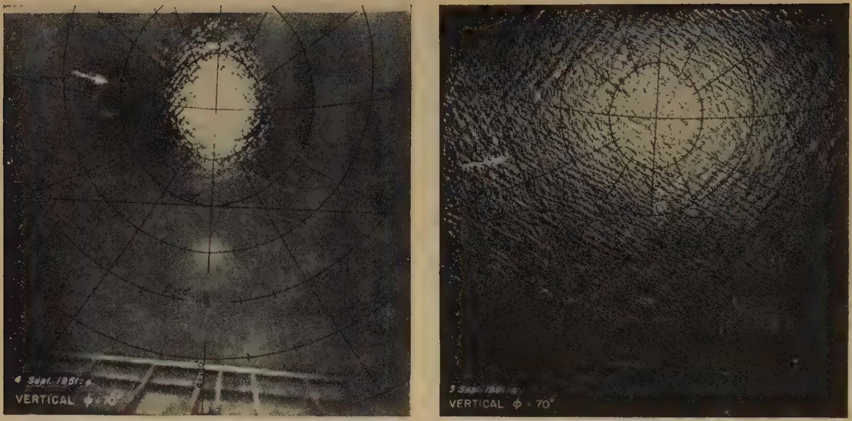

Fig. 1. Glitter patterns photographed by aerial camera pointing vertically downward at solar elevation of $\phi = 70°$. The superimposed grids consist of lines of constant slope azimuth α (radial) drawn for every 30°, and of constant tilt β (closed) for every 5°. Grids have been translated and rotated to allow for roll, pitch, and yaw of plane. Shadow of plane can barely be seen along $\alpha = 180°$ within white cross. White arrow shows wind direction. *Left:* water surface covered by natural slick, wind 1.8 m sec^{-1}, rms tilt $\sigma = 0.0022$. *Right:* clean surface, wind 8.6 m sec^{-1}, $\sigma = 0.045$. The vessel *Reverie* is within white circle.

2. THE OBSERVATIONS

Aerial Observations

The derivation of Sec. 4 will show that the radiance of reflected sunlight from the sea surface is determined by the probability distribution of slopes provided the light is reflected only once. To avoid multiple reflections we have made measurements only when the sun was high (only slopes greater than about one-half the angle of sun elevation can cause a second reflection). For a high sun the glitter pattern covers the surface to all sides of a point directly beneath the observer, and aerial observation is indicated.

A B-17G airplane was made available from the 3171st Electronics Research and Development Group, Griffiss Air Force Base, Rome, New York. Four K-17 (six-inch focal length) aerial cameras were mounted on a frame which could be lowered through the bomb bay and leveled during flight. They were wired for synchronous exposures. Two cameras pointed vertically downward, the other two pointed to port and were inclined downward at an angle of 30° with the horizontal. This allowed for a 25 percent overlap between the vertical and tilted photographs. One of the vertical cameras and one of the tilted cameras took ordinary in-focus or *image* photographs (see Fig. 1) using "variable density minus blue" filters. At an altitude of 2000 feet two points on the sea surface separated by more than 40 cm are resolved on the image photographs. The two remaining cameras took *photometric* photographs. From these cameras the lens systems had been removed, and glass sandwich filters containing Wratten gelatin A-25 absorbers installed.

During the photographic runs, the plane was steered by sun compass so that the azimuth of the tilted cameras was toward the sun. An attempt was made to avoid cloud shadows and atmospheric haze. In most cases the field of the cameras was sufficiently restricted to avoid these effects when the plane was flying at an altitude of 2000 feet.

Observations at Sea

In order to correlate measurements of wind speed with slope distribution free from modifying effects of land it was necessary to have meteorological records from a vessel near the location of the photographs. For this purpose a 58-foot schooner, the *Reverie*, was chartered and equipped with anemometers on the foremasthead (41 feet above sea level) and the bowsprit (9 feet). The signal from the anemometers was smoothed with an electrical low-pass filter having an 18-second time constant, then recorded. Wind direction was estimated by eye. Other measurements included the air and water temperatures, and the wet and dry bulb temperatures.

One of the objects of this investigation was to study the effect of surface slicks. First we attempted to spray powdered detergent from the vessel and later from the plane, but the slicks thus produced did not persist sufficiently. A satisfactory solution was to pump oil on the water, using a mixture consisting of 40 percent used crankcase oil, 40 percent Diesel oil, and 20 percent fish oil. With 200 gallons of this mixture a coherent slick 2000 feet by 200 feet could be laid in 25 minutes, provided the wind did not exceed 20 mph.

Location of Observations

During July, 1951, observations were taken offshore from Monterey, California, where a variety of wind

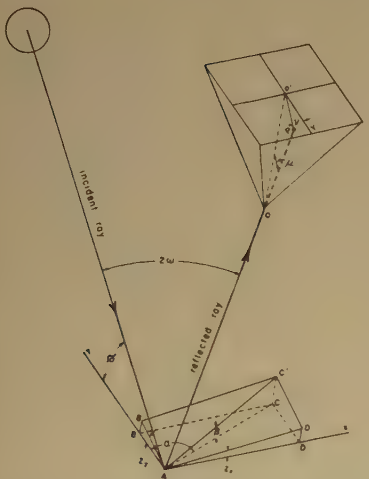

FIG. 2. The coordinate system is centered at the sea surface with the z-axis vertically upward (not shown) and the y-axis drawn horizontally toward the sun. The incident ray is reflected at A and forms an image at P on a horizontal photographic plate. Points A, B, C, and D define a horizontal plane through A and $AB'C'D'$, the plane tangent to the sea surface. The tilt β is measured in the direction AC of steepest ascent, and this direction makes an angle α to the right of the sun. OO' is parallel to the z-axis and $O'Y'$ to the (negative) y-axis.

conditions could be expected. Unfortunately the number of clear days was even smaller than given on climatological charts, and only two successful flights were completed.

By the end of July the sun elevation at noon was approaching our minimum requirement of 55° (to photograph plane's shadow; see Sec. 3), and it was decided to move the plane and vessel south to Hawaii. In this area one can select radically different wind conditions by moving short distances. The island of Maui was chosen because the region surrounding this island is the least clouded. Also, the harbor and airport facilities are conveniently near to one another. Conditions were excellent, and all observations were taken during the period August 25 to September 25, 1951.

3. THE GEOMETRY OF REFLECTION

The geometry of reflection has been considered by Minnaert[4] and Van Wieringen[5] with special emphasis on circular waves also by Hulbert[2] and by Eckart.[6] Here we shall require a systematic development which can be readily expanded into the second order calculations of the next section. The slope vector has the components (Fig. 2)

$$z_x = \partial z/\partial x = \sin\alpha \tan\beta, \quad z_y = \partial z/\partial y = \cos\alpha \tan\beta, \quad (1)$$

where α is the azimuth of ascent (clockwise from the sun) and β is the tilt.† A unit vector normal to the surface and positive upwards has the components

$$a_n = -\sin\alpha \sin\beta, \quad b_n = -\cos\alpha \sin\beta, \quad c_n = \cos\beta.$$

The unit vector along the incident ray has the components

$$a_i = 0, \quad b_i = -\cos\phi, \quad c_i = -\sin\phi,$$

and along the reflected ray

$$a_r = -\sin\nu \sin\mu, \quad b_r = -\cos\nu \sin\mu, \quad c_r = \cos\mu.$$

According to the law of reflection the vector difference between the reflected and incident rays must lie along the surface normal:

$$\begin{aligned} a_r - a_i = 2a_n \cos\omega, \quad b_r - b_i = 2b_n \cos\omega, \\ c_r - c_i = 2c_n \cos\omega, \end{aligned} \quad (2)$$

where $2\cos\omega$ is the proportionality constant. Squaring, adding, and making use of $a^2+b^2+c^2=1$ gives

$$\cos\omega = \cos\beta \sin\phi - \cos\alpha \sin\beta \cos\phi. \quad (3)$$

It can be verified that ω is the angle of incidence or reflection (Fig. 1). Equations (2) now yield the "grid" relations‡

$$\begin{aligned} \cos\mu &= 2\cos\beta \cos\omega - \sin\phi, \\ \cot\nu &= \cot\alpha - \tfrac{1}{2}\csc\alpha \csc\beta \sec\omega \cos\phi. \end{aligned} \quad (4)$$

For any chosen orientation of the camera the angles μ, ν can be readily converted to film coordinates, and lines of constant α and β constructed (see Fig. 1). The grids are independent of the height of the camera, but depend on the solar elevation ϕ. The effect of the setting sun is to concentrate the pattern along a narrow street.

All photographs have been corrected for the roll, pitch, and yaw of the plane. With some care in flying, these angles can all be kept to within a few degrees. The correction then consists of a translation of the grid in order that the horizontal specular point on the grid coincides with that on the photograph, and a rotation so that the line $\alpha = 0$ points toward the sun. The translation and rotation are uniquely determined from the positions on the photographs of the plane's shadow (clearest on Fig. 1, upper left) and of the horizon, allowance having been made for the depression of the horizon due to the earth's curvature. The formulas can be found in Sec. (3.1) of Cox and Munk.[7]

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[4] M. Minnaert, Physica 9, 925 (1942).

[5] J. S. Van Wieringen, Proc. Koninkl. Ned. Akad. Wetenschap. 50, 952 (1947).

[6] Carl Eckart, The sea surface and its effect on the reflection of sound and light. University of Calif. Div. of War Research No. M407, March 20, 1946 (unpublished). The horizontal extent of the glitter pattern is assumed small compared to the distance from the observer.

† In geologic literature the attitude of a surface is described by its dip and strike. The former equals numerically the inclination angle β; the latter is measured 90° to the left (looking uphill) of α.

‡ In terms of other parameters the grid relations can become surprisingly complicated. In fact, Shuleikin (reference 3) considered the computation of such grids as "incommodious" and constructed them experimentally by projecting onto a screen the reflection from mirrors of constant slope.

[7] C. Cox and W. H. Munk, Scripps Inst. of Oceanogr. Bull. (to be published).

4. SURFACE RADIANCE

Up to now we have considered ordinary "in focus" photographs, or *image photographs*. These photographs show the presence of whitecaps, slicks, and cloud shadows. They also provide the basis for correcting for the roll, pitch, and yaw of the plane. Simultaneously with the tilted and vertical image photographs, and covering the identical fields of view, we have photographed the sea surface with two additional cameras from which lenses had been removed. The resulting out-of-focus photographs, or *photometric photographs*, provide the basis for computing frequency distributions of slope.

At the horizontal specular point the sea surface is likely to be so bright as to be blinding to the eye, whereas at some distance from this point the surface is much darker. The principal reason for this variation is that the gentle slopes (which are required for highlights near the horizontal specular point) occur more frequently than the steep slopes. On the *photometric photographs* the glitter pattern appears therefore as a round blob with a bright core (on the positive print), and gradually diminishing intensity to the outside. The density of the blob (on the negative) is then measured with a densitometer at points corresponding to the intersection of appropriate grid lines.

But there are other factors, in addition to the slope distribution, which help determine the density of the photograph. These are (1) the tolerance of slopes for the occurrence of a highlight at a fixed point, as related to the finite size of the sun; (2) the dependence of the coefficient of reflectivity of the water surface on the angle of incidence; (3) the ratio of sea surface area to the corresponding area on the photograph, for different points on the photograph; (4) the variable sensitivity of the camera to light from various directions; (5) the dependence of the film density on the exposure. These factors will now be considered.

4.1. The Tolerance Ellipse

Let the point z_{x0},z_{y0} on an z_x,z_y diagram (Fig. 3) represent the required slope at x_0,y_0 on the sea surface in order that a light beam from the sun's center striking this point be reflected into the camera. In order for x_0y_0 to be a highlight for a point source of light on the sun's periphery, the values z_{x0} and z_{y0} must vary by small quantities z_x' and z_y'. As the light source moves about the sun's periphery, it will trace an ellipse centered at z_{x0},z_{y0} on the z_x,z_y diagram. This ellipse defines a tolerance in possible values of z_x,z_y for a highlight at x_0,y_0.

It may be shown[7] that the area of the tolerance ellipse is

$$\Delta_t=\tfrac{1}{4}\pi\epsilon^2\sec^3\beta_0\sec\omega_0, \qquad (5)$$

where $2\epsilon=32'.0$ is the angular diameter of the sun, and β_0,ω_0 the angles of tilt and incidence at the center of the highlight. The derivation assumes that the solid angle subtended by the highlight at the observer is small

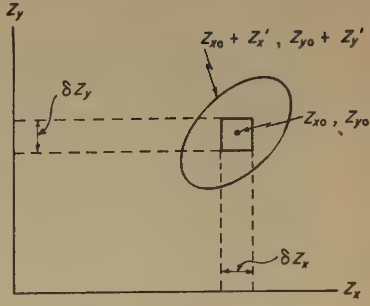

FIG. 3. The tolerance ellipse.

compared with $\pi\epsilon^2$, the solid angle subtended by th sun. This condition is always satisfied for an aeri observer.

The tolerance ellipse relates the probability for th occurrence of a certain slope to the probability P for highlight to occur in a certain area. Suppose we wis to find the probability $p(z_{x0},z_{y0})\delta z_x\delta z_y$ of slopes in th interval $z_{x0}\pm\frac{1}{2}\delta z_x$, $z_{y0}\pm\frac{1}{2}\delta z_y$ (Fig. 3). The probability slopes occurring within the tolerance ellipse of are $\Delta_t(z_{x0},z_{y0})$ centered at z_{x0},z_{y0} equals

$$P(z_{x0},z_{y0})=p(z_{x0},z_{y0})\Delta_t(z_{x0},z_{y0}).$$

Thus if P can be measured, p can be readily compute

The determination of P is a matter of some dif culty. One method would consist of recording the fra tion of time, P, during which x_0,y_0 is a highlight, b this is difficult to accomplish from a plane. A measur ment that comes closer to being feasible is the determ nation of the fraction of horizontal area in the immed ate vicinity of x_0,y_0 that is highlighted during a ve brief interval. This fraction is again equal to P, pr vided that in this vicinity all points have equal *a pri* probabilities of attaining a given slope. This provisi excludes the edge of slicks, or regions where win change rapidly. The observer must be sufficiently hi that the "vicinity" of x_0,y_0 includes an area larger linear dimensions than the wavelength of the longe ocean swell present.

Yet not even the fractional area that is highlight can be measured directly from the photographs. In t first place, the individual glitters are too small to resolved on the aerial photographs; what appears an isolated highlight is actually a cluster of seve hundred tiny glitters, each perhaps a millimeter diameter. In the second place, the photographic ima of a cluster is, because of its high intensity, many tim larger than the image that would be obtained with perfect optical system.

However, by means of the out-of-focus, or densi photographs we can determine the *average* radiance o an area which includes many clusters of highligh But the required quantity is the fractional area that highlighted. Fortunately, the radiance and the fr tional area are proportional, and the latter can be computed from the former. The required relationship is derived in the next section.

4.2. The Scattering Cross Section

Let Δ_h designate the area of a single highlight projected onto a horizontal plane; then $\Delta_h \sec\beta$ will be the actual area on the (sloping) sea surface, and $\Delta_h \sec\beta \cos\omega$ the projection onto a plane normal to the incident rays. Let δH be the irradiance at the sea surface from a small surface element on the sun. The incident flux upon the highlight from this element is $\delta H \Delta_h \sec\beta \cos\omega$. The reflected flux is $\rho(\omega)\delta H \Delta_h \sec\beta \cos\omega$, where ρ is the reflection coefficient; it is radiated into a solid angle $\pi\epsilon^2$, the solid angle subtended by the sun. This result follows by reciprocity, as we have already shown that a bundle of parallel rays from the camera to the periphery of the highlight will be reflected around the periphery of the sun. Hence the intensity of the reflected beam (in power per unit solid angle) equals $\rho(\omega)\Delta_h \delta H(\pi\epsilon^2)^{-1} \sec\beta \cos\omega$. Since the camera aperture lies within the solid angle $\pi\epsilon^2$ regardless of the location of the element on the sun's surface, we can sum surface elements and replace δH by H, so that

$$J=\rho(\omega)\Delta_h H(\pi\epsilon^2)^{-1} \sec\beta \cos\omega \tag{7}$$

is the reflected radiant intensity from *one* highlight.[§] From a horizontal unit area of sea surface containing many such highlights and yet sufficiently small so that β can be considered constant from highlight to highlight, the reflected radiant intensity is

$$N \cos\mu = PJ, \tag{8}$$

since P represents the fraction of surface that is highlighted under the assumption previously stated. Combining (5) to (8) yields the desired relation

$$p=4\rho^{-1}(\cos^4\beta)N \cos\mu/H. \tag{9}$$

The quantity N is the radiance of the sea surface in the line of sight, and the ratio $N \cos\mu/H$ has been called by Eckart[8] the "scattering cross section for unit solid angle per unit area of sea surface."

4.3. The Reflection Coefficient

The reflection coefficient $\rho(\omega)$ for unpolarized light at a dielectric interface is given by Fresnel's formula

$$2\rho(\omega)=\sin^2(\omega-\omega') \csc^2(\omega+\omega') + \tan^2(\omega-\omega') \cot^2(\omega+\omega'), \tag{10}$$

where $\sin\omega = m \sin\omega'$ and m is the ratio of indices of refraction across the interface. For uncontaminated sea water $m=1.338$, yielding $\rho(\omega)=0.020$, 0.021, 0.060 and 1.00 for $\omega=0°$, 30°, 60°, and 90°.

In the presence of slicks (Fig. 1, left) these values have to be somewhat modified. The artificial slicks laid by the boat consisted of a mixture of crankcase oil, sardine oil, and kerosene. The reflection at normal incidence is $\rho(0)=(m-1)/^2(m+1)^2$. For orientation, we consider monodecane with the refractive index 1.42. This gives $\rho_1(0)=0.030$ for air-monodecane, and $\rho_2(0)=0.001$ for the monodecane-water interface.

It is found that the thickness of the artificial slicks was of the order of several wavelengths of light, and about a thousand times the thickness of a monomolecular layer. By assuming that both faces of the oil layer reflect light according to Fresnel's law, the complete reflection coefficient (taking into account multiple reflections but disregarding interference effects) equals $\rho_1+\rho_2(1-\rho_1)^2(1-\rho_1\rho_2)^{-1}$ for normal incidence. This gives 0.031 for monodecane, as compared to 0.020 for an uncontaminated water surface. The computed increase in reflectivity is in general agreement with the observed increase over artificial slicks.

Natural slicks are probably much thinner, perhaps only a few molecules thick.[||] The effect on the reflection of light should then be negligible, and Eq. (10) should apply with $m=1.338$. This has been confirmed by photometric measurements at normal incidence.

4.4 Photographic Photometry

The remaining problem is to relate the sea surface radiance $N \cos\mu$ to the film density D. There are some difficulties in the use of aerial cameras for photometry.

The photometric cameras were provided with red glass filters, and had a camera aperture of 1.7 cm. A point source (or any highlight) then has a nearly circular image with a diameter of about 1.7 cm. This size fulfills the following conditions: (1) it is large compared to the average distance between highlights, so that the highlights blend into one another and the grayness of the negative is not too spotty; (2) it is large compared to the size of the measuring aperture of the densitometer; (3) it is not large compared to the grid interval between isoclines and isogons.

Suppose s is the distance from the highlighted area (OA in Fig. 2), d is the diameter of the aperture, and λ the angle between the principal axis of the camera and the reflected ray [$\lambda=\mu$ for an exactly vertical camera (Fig. 2)]. The solid angle subtended by the aperture is $\frac{1}{4}\pi d^2 s^{-2} \cos\lambda$. Then since $N \cos\mu$ is the flux of radiation from a unit sea surface into a unit solid angle, $\frac{1}{4}\pi d^2 s^{-2}\tau(\lambda)N \cos\lambda \cos\mu$ is the corresponding flux into the photosensitive emulsion.

The transmission $\tau(\lambda)$ allows for (1) the reflection of the incoming rays by the outer face of a filter; (2) by the inner face; (3) absorption of flux in the filter;

[§] This result follows also from the general theorem that the incident and reflected powers per unit area per unit solid angle are equal for a perfect reflector.

[8] C. Eckart, J. Acoust. Soc. Am. 25, 566 (1953). Here the linearized equations are developed for the case where the incoming radiation is not necessarily short compared to the ocean waves. For the limiting case of short-wave radiation, Eckart obtains essentially $p=4\rho^{-1}(N \cos\mu/H)$.

[||] Preliminary measurements by Kittredge indicate monomolecular slicks.

(4) reflection by the gelatin on the photographic plate; and (5) the vignetting effect resulting from the finite width of the aperture. The index of refraction of glass and the gelatin is 1.52, and hence each of the effects (1), (2), and (4) is proportional to $1-\rho(\lambda)$, where $\rho(\lambda)$ is Fresnel reflectivity, Eq. (10). Altogether the intensity is therefore reduced by a factor $[1-\rho(\lambda)]^3$.

The absorption of energy by the red filter consists first of a constant term involving the absorption of solar power for wavelengths less than 580 mμ. Of the energy in the band 580 mμ to 660 mμ, 20 percent is absorbed in the case of normal incidence and 24 percent for a ray traveling obliquely through the filter to the corner of the photograph. Wavelengths greater than 660 mμ are unimportant since the film is not sensitive to them.

The vignetting effect was computed from the dimensions of the aperture. The computation was checked by measuring the deviation from a circle of an image formed by a point source. All of these effects combined result in a ratio $\tau(45°)/\tau(0°)=0.81$ between the transmission at the extreme corner of the photograph and that at the center.

The product (flux) (exposure time) gives the luminescent energy reaching a unit film area during the entire exposure from a unit area of sea surface. Altogether this unit area of film receives energy from Δ_u unit areas of sea surface amounting to

$$E=\tfrac{1}{4}\pi d^2 s^{-2}\tau(\lambda)t\Delta_u \cos\lambda \cos\mu \qquad (11)$$

units of luminescent energy in an exposure of duration t. It can be shown that $\Delta_u=s^2f^{-2}\cos^3\lambda \sec\mu$, where f is focal length, and therefore,

$$\begin{aligned} N&=C\sec^4\lambda(\tau)^{-1}E(D),\\ C&=(4f^2)/(\pi d^2 t). \end{aligned} \qquad (12)$$

The photometric photographs were placed over the appropriate grids (translated and rotated to allow for roll, pitch, and yaw), and the intersections for every ten degrees of α and five degrees of β marked on the films. Additional intersections were marked for low winds and slick sea surface. The density D at each marked position was measured by a Welch "Densichron." The reproducibility of these measurements was ±0.02 in density.

Additional measurements of density were made on each set of photometric photographs at corresponding points of the overlapping regions between the tilted and vertical films. Comparison of these pairs of densities was the basis of adjusting the calibrations for tilted and vertical films to common (but still arbitrary) units, and to remove any inconsistencies between the two calibrations.

The exposure $E(D)$ was determined from the density D of the film by comparison with the density produced by a light of known intensity. Because of the failure of the reciprocity law the calibration exposure had to be the same as the exposure on the flights. The calibration light source consisted of a concave diffusing surfa (from a Federal 4-in.×5-in. cold light enlarger) illun nated by 39 incandescent bulbs arranged in a ri within the periphery of the diffusing surface. T calibrating light was passed through a Wratten A- filter in order to restrict the wavelength range to tho of the photometric photographs. (Sunlight reflect from white blotting paper gave similar results.) Befo falling on the photographic film the light source w intercepted by an optical wedge (a modified Eastma Kodak projection print scale) with eleven steps differing transmission ranging from 100 to 3.7 percer The range of light intensities (100 to 3.7) from a sing calibration was extended by making several exposur with differing voltages on the incandescent lamp Curves of D *versus* $\log E$ were drawn for each exposu and fitted together by comparison of the overlappi range of densities. In this way a calibration range light intensities of 1000 to 1 was obtained.

Calibrations were made before and after each fligh The roll film (super XX with 9-in.×9-in. negatives) w developed in motor-driven tanks using D-76 develope On a roll containing only calibration exposures it w found that the slopes, γ, of the D-$\log E$ curves vari by less than 3 percent except for exposures within 12 of the ends of the roll. Consequently leaders of th length were left on the ends of all photometric phot graph rolls. Sets of calibration exposures were made the beginning and end of each roll and at interva within the roll so that there were never more than photometric photographs between calibrations. Becau of various malfunctions of the developing machines, t various calibrations on one roll gave values of γ varyi by as much as 10 percent. The development of t photometric photographs was carried out to a γ about 0.8. With this development the film was able register light whose intensity varied over a range more than 1000 to 1.

4.5. Relationship between Probability and Film Densities

Equation (9) expresses the slope probability p as function of surface radiance N, and (12) relates N the film density D. These are the desired relationshi For the special case of the sun overhead and the came *exactly* vertical, $\phi=90°$, $\mu=\lambda=2\beta$, and $p\sim\cos^4\beta \sec^3\mu$ or $p\sim(1+\mu^2+\cdots)E$ for the probability distribution small slopes. This linear relation (to a first orde between probability and exposure indicates the inhere soundness of the present method.

5. BACKGROUND RADIATION

In addition to the reflection of the sun's rays fro the sea surface, there are two other distinct sources radiation: (1) the skylight reflected at the sea surfa and (2) the sunlight scattered by particles beneath t sea surface. These provide the "background" agai which the sun's glitter is measured.

On calm days, the scattered sunlight and reflected skylight are of roughly equal intensity directly beneath the plane. In this region it is difficult to recognize the configuration of the sea surface outside of the glitter pattern for two reasons: (a) the scattered light is nearly independent of the presence of waves; and (b) the sky reflection shows little contrast on different sides of waves because the reflected parts of the sky dome are about equally bright and the coefficient of reflection varies little from that for normal incidence. The skylight predominates at greater distances. One qualitative indication of the scattered sunlight is the existence of the plane's shadow outside the limits of the glitter pattern (Fig. 2).

In this section, rough estimates are made of these two sources of background radiation. On the basis of these estimates correction factors are introduced. Fortunately the ratio of signal to background can be made fairly large by the use of a red filter, because sunlight is white while the skylight and scattered light is blue. Near the horizontal specular point the ratio varies from 500:1 on a smooth sea to 15:1 on a very rough sea. But in computing the probability of the large (and infrequent) slopes, our method is essentially limited by the disappearance of the glitter radiation into the background of the reflected skylight and scattered sunlight.

5.1. The Reflected Skylight

We consider the fraction $p(z_x,z_y)\delta z_x\delta z_y$ of a small (horizontal) unit area of sea surface for which the slope is within the limits $z_x\pm\frac{1}{2}\delta z_x$, $z_y\pm\frac{1}{2}\delta z_y$. The corresponding actual area within these limits is $\sec\beta p\delta z_x\delta z_y$, and the area projected normal to the line of sight is $\cos\omega\sec\beta p\delta z_x\delta z_y$.

Let the radiation incident onto the sea surface from the sky be characterized by its radiance N_s. The reflected radiance is $N_s\rho(\omega)$. We assume the light is reflected only once. Hence the radiant intensity at a great distance from this fractional part of the sea surface is $N_s\rho(\omega)\cos\omega\sec\beta p(z_x,z_y)\delta z_x\delta z_y$. The radiance due to all slopes is then

$$N'=\sec\mu\int\int N_s\rho(\omega)\cos\omega\sec\beta p(z_x,z_y)dz_xdz_y, \quad (13)$$

the limits of integration being such that all visible slopes are included. Equations (13) and (9) are the corresponding expressions for radiance due to skylight and sunlight.

The procedure for evaluating the integral is as follows: We anticipate (Sec. 6) that to a first order the slopes are normally distributed and independent of wind direction according to $p=(\pi\sigma^2)^{-1}\exp-(z_x^2+z_y^2)/\sigma^2$ where σ is the rms slope regardless of direction. As a rough approximation the sky dome is assumed uniform, $N_s=$constant. A rotated coordinate system is set up with the y' axis drawn in the direction of the small area of sea surface for which the radiance is sought. In this coordinate system

$$\cos\omega=\cos\beta(\cos\mu+z_y'\sin\mu).$$

Other terms in (13) remain unchanged. The quantities $F(\omega)=\rho(\omega)\cos\omega$ and $\sec\beta=(1+z_x'^2+z_y'^2)^{\frac{1}{2}}$ may now be expanded in Taylor's series in z_x',z_y' around the values $z_x'=z_y'=0$, for which $\beta=0$, $\omega=\mu$. This yields

$$N'=(\pi\sigma^2)^{-1}N_s\rho(\mu)\int\int(1+az_y'+bz_y'^2+cz_x'^2+\cdots)$$
$$\times\exp[-(z_x'^2+z_y'^2)/\sigma^2]dz_x'dz_y', \quad (14)$$

where

$$a=-(F'/F),\quad b=\tfrac{1}{2}+\tfrac{1}{2}(F''/F),\quad c=\tfrac{1}{2}+\tfrac{1}{2}(F'/F)\cot\mu.$$

The functions F, $F'=dF/d\omega$ and $F''=d^2F/d\omega^2$ are evaluated at $\omega=\mu$.

If all slopes are less than $90°-\mu$, then the sea surface is everywhere visible, and the limits of integration are essentially $\pm\infty$. Large negative slopes in the component z_y' are not visible if they exceed $\cot\mu$ in magnitude. We shall allow for this "first-order" hiding by setting the limits $(-\cot\mu)$ to ∞ for z_y' (but $\pm\infty$ for z_x'). This is equivalent to the limits 0 to $\frac{1}{2}\pi$ in the angle of incidence ω. Because some additional slopes are hidden, the computed value of N' will be somewhat too large for large μ. But the evaluation of the "second-order" hiding involves information on the spectrum of ocean waves, and in the absence of such information we must restrict ourselves to the first-order hiding. The approximation will be adequate for large values of the dimensionless parameter

$$k=\sigma^{-1}\cot\mu. \quad (15)$$

The integration between the indicated limits yields

$$N'=N_s\rho(\mu)\{\tfrac{1}{2}[1+I(k)]+\tfrac{1}{2}\pi^{-\frac{1}{2}}a\sigma e^{-k^2}$$
$$+\tfrac{1}{4}b\sigma^2[1+I(k)-2\pi^{-\frac{1}{2}}ke^{-k^2}]$$
$$+\tfrac{1}{4}c\sigma^2[1+I(k)]+\cdots\}, \quad (16)$$

where

$$I(k)=2\pi^{-\frac{1}{2}}\int_0^k e^{-t^2}dt$$

is the error integral.

So far we have neglected multiple reflections. If in the case of the *final* reflection the incident ray comes from *beneath* the horizon, then certainly there must have been at least one preceding reflection. The condition for this "first-order" multiple reflection is that z_y' be negative and exceed $\frac{1}{2}\cot\mu(1-\tan^2\beta)$ in magnitude. The product of coefficients of reflection of all but the last reflection is unknown but must lie between zero and unity. In the latter extreme case multiple reflections would not alter the radiance, and Eq. (16) is correct as it stands. In the former extreme case, the limits of integration in (13) must be replaced by $-\frac{1}{2}\cot\mu(1-\tan^2\beta)<z_y'<\infty$. These can be replaced by the limits $-\infty<z_x'<\infty$, $-\frac{1}{2}\cot\mu<z_y'<\infty$ because of the heavy discrimination of the exponential factor in the integrand against contributions from large β. The result of this integration is again Eq. (16) but with

$$k = (2\sigma)^{-1} \cot\mu \qquad (17)$$

in place of (15).

Figure 4 shows the radiance of the sea surface as bracketed by these two expressions. In Figs. 5 and 6 curves of $N' \cos\mu$ are plotted against some experimental values for a calm and a moderately rough sea, respectively. On the calm day the reflected skylight can account for only slightly more than half of the background intensity near $\mu = 0$.

5.2. The Scattered Sunlight

The above discrepancy is assumed to be due to scattered light from within the water. Qualitative evidence for the importance of scattered sunlight is given by the appearance of the plane's shadow outside of the glitter. Within the shadow the background radiance is reduced because of the absence of back-scattered light, whereas the reflected skylight is not appreciably diminished.

An empirical relationship for the scattered sunlight as a function of μ was obtained by subtracting from the total measured background that amount due to the reflected skylight (Fig. 5). Two particular photographs (3 Sept *j*, 4 Sept *e*, Fig. 1, left) were chosen because the glitter was the smallest on record, and there was adequate space on the photographs to measure the background outside the glitter. It is found that the scattered sunlight is strongest directly beneath the plane ($\mu = 0$), and decreases with increasing μ more rapidly than $\cos\mu$ but less rapidly than $\cos^2\mu$. A comparison of the photographs for 3 Sept *j* and 4 Sept *e* shows that the scattered sunlight is proportional to irradiance of the sun, as might be expected.

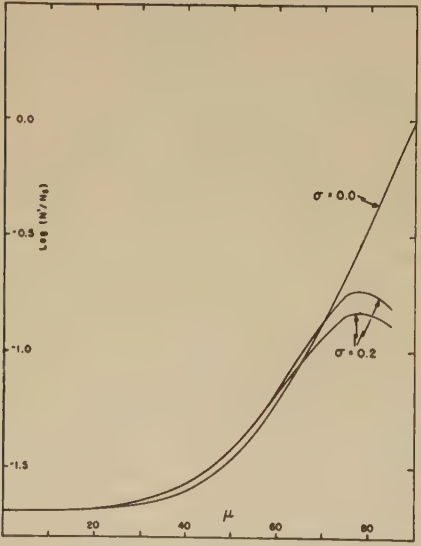

FIG. 4. The radiance (in arbitrary units) of a smooth sea surface ($\sigma = 0$) and a rough sea surface ($\sigma = 0.2$), according to Eq. (16). The two branches of the latter curve for large μ correspond to two extreme assumptions regarding multiple reflections.

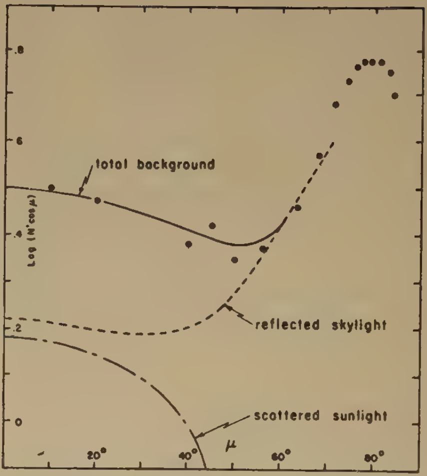

FIG. 5. The solid circles show the measured background on a very calm day (3 Sept *j*, $\sigma = 0.091$), when the glitter pattern was confined to a small portion of the photograph. This background is due partly to reflected skylight, partly scattered sunlight, as shown.

5.3. Correction for Background

In the following procedure for allowing for skylight and scattered sunlight it will be assumed that the empirical law for the scattered sunlight is independent of the roughness of the sea surface, but depends only on the irradiance H from the sun. Measurements of the glitter (uncorrected for skylight) are used to determine σ and H to a first approximation. Using this value of H, the curve for the scattered sunlight is drawn (Fig. 6). Then measurements on the tilted photograph of skylight intensity from regions outside the glitter (Fig. 6, solid circles) are used to fix the sky intensity. By means of the curves of Fig. 4, sky reflection is extrapolated to $\mu = 0$ using the appropriate value of σ. The curves for scattered sunlight and reflected skylight are then combined to give the total background as function of μ. Finally, this background is subtracted from the observed radiance.

On photographs taken at high wind speeds, the glitter pattern covers the entire field of view of both tilted and vertical cameras. Intensities from regions where the glitter reflection is weak give a basis for finding an upper limit to the background light. In all cases it has been found that the upper limit of the ratio of total background intensity to sun intensity varies by less than 30 percent. The indication then is that the upper limit of the background is not far in excess of the real background.

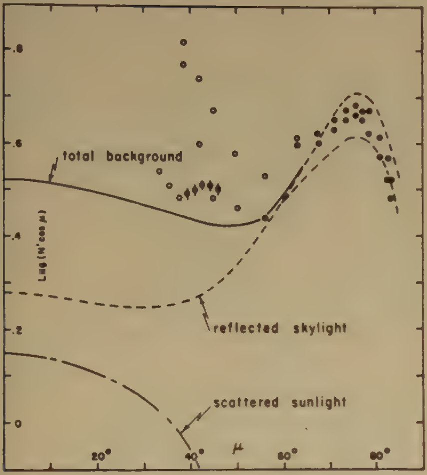

FIG. 6. The background radiation (in arbitrary units) on a moderately rough day (4 Sept k, $\sigma=0.13$). The solid circles correspond to measurements outside the glitter pattern. The open circles contain some glitter radiation, and lie, therefore, above the background curve. Circles with the vertical line correspond to measurements on the vertical photograph, the other circles to measurements on tilted photograph.

6. STATISTICS OF SLOPE DISTRIBUTION

The log of the unnormalized probability (corrected for background) at the various α,β-grid intersections has been tabulated for each set of photographs. A typical set of measurements—not the best—is shown in Fig. 7 and will be used as an example in the following discussion.

Rather than presenting tabulated values, it is more compact to present the results in analytical form as a function of wind speed, and thus bring out the essential physical content. In this way the experimental error is also subdued. A reasonable approach is to make use of the fact that the distribution is close to Gaussian. By representing the data as a Gram Charlier series we can develop the deviation from the normal distribution in a systematic manner. These deviations represent skewness and peakedness and therefore have a simple physical interpretation.

6.1. The Gram Charlier Series

The Gram Charlier distribution[9] in two dimensions assumes the form

$$p=[\text{two-dimensional Gaussian distribution}]$$
$$\times\Big[1+\sum_{i,j=1}^{\infty} c_{ij}H_i(\xi)H_j(\eta)\Big].$$

The summation on the right represents the deviation from a normal distribution. It consists of products of Hermite polynomials H_iH_j with coefficients c_{ij} to be determined. The arguments ξ,η are defined below. The Gaussian distribution is represented in general by a product of three exponentials: two are functions of the two slope components separately and the third a function of their cross product. By a suitable rotation from the "sun x,y-system" it is always possible to suppress the cross-product term. This defines the principal axes, x',y'. As is to be expected, one of the principal axes is found to be parallel to the wind direction. The y' axis is arbitrarily defined to be this axis and to point upwind.

Some simplification of the summation term results from two empirical facts: (1) From many studies it is known that the mean slope is negligible over an area whose linear dimensions are much greater than the longest ocean wavelength. Hence $\langle z_x'\rangle_{\mathrm{Av}}=\langle z_y'\rangle_{\mathrm{Av}}=0$. (2) There is no asymmetry crosswind. This result follows from our own observations (Sec. 6.2).

A further simplification results by using the "standardized" slope components

$$\xi=z_x'/\sigma_c, \quad \eta=z_y'/\sigma_u,$$

where¶ σ_c and σ_u are the rms values of z_x' and z_y', respectively. The Gram Charlier distribution now assumes the form

$$\begin{aligned} p(z_x',z_y')=(2\pi\sigma_c\sigma_u)^{-1}\exp-\tfrac{1}{2}(\xi^2+\eta^2) \\ \times\big[1-\tfrac{1}{2}c_{21}(\xi^2-1)\eta-\tfrac{1}{6}c_{03}(\eta^3-3\eta) \\ +(1/24)c_{40}(\xi^4-6\xi^2+3) \\ +\tfrac{1}{4}c_{22}(\xi^2-1)(\eta^2-1) \\ +(1/24)c_{04}(\eta^4-6\eta^2+3)+\cdots\big]. \quad (18)\end{aligned}$$

For slopes up to $\xi=\eta=2.5$ the present expansion is adequate. The rms slopes σ_c,σ_u, the skewness coefficients c_{21},c_{03}, and the peakedness coefficients c_{40},c_{22},c_{04} are to be evaluated from the data.

The procedure followed was to represent the data in the form of $\log p$, the *probability index*, as a Fourier series in α for fixed values of the tilt β. The amplitudes of the harmonic terms were then expressed as power series in the tilt. This permitted an analytic representation of the probability index for each photograph even where data were missing because of obscuring of glitter by whitecaps or slick patches. The connection between the power series coefficients and the rms slopes, and skewness and peakedness coefficients of Eq. (18) has been established[7] and in this indirect way the Gram Charlier series was fitted to the empirical data. Since the Gram Charlier series is normalized, no previous normalization of the probability was necessary.

6.2. Orientation of the Principal Axes

It will be seen from Fig. 7 that a Fourier analysis of the probability as a function of α (β=constant) will have a pronounced second harmonic. This feature has been used to rotate the x,y axes (the sun system) through an angle χ to the x',y' axes (the wind system) for which the probability distribution reduces to the form of Eq. (18). After fitting data to this form it was found (1) that the rotated y' axis points nearly into the direction of the wind** and (2) that the residuals (illustrated by the difference between the data points and the curves of Fig. 7) were reduced to "noise level."

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[9] For example, Harald Cramer, *Mathematical Methods of Statistics* (Princeton University Press, Princeton, 1946). This gives a general account, but the development in two dimensions could not be found in the literature. Details are given in reference 7.

¶ The subscripts "c" and "u" refer to crosswind and upwind, respectively.

The conclusions are (1) that the principal axes are in the direction of the wind and crosswind; (2) that there is no asymmetry crosswind. The observed wind direction and the empirical bearing of the positive y' axis (χ+sun azimuth) are summarized in Table I.

6.3. Mean Square Slopes

The mean square slope components, crosswind and up/downwind, were computed for each set of photographs (Table I). The two components, and the mean square slope $\sigma_c^2+\sigma_u^2$ (regardless of direction) vary nearly linearly with the wind speed W (in m sec^{-1}) recorded at 41 feet above sea level. The regression lines and correlation coefficients r have been computed by the method of least squares:

clean surface

$$\sigma_c^2 = 0.003+1.92\times10^{-3}W\pm0.002 \qquad r=0.956$$

$$\sigma_u^2 = 0.000+3.16\times10^{-3}W\pm0.004 \qquad r=0.945$$

$$\sigma_c^2+\sigma_u^2 = 0.003+5.12\times10^{-3}W\pm0.004 \qquad r=0.986$$

slick surface

$$\sigma_c^2 = 0.003+0.84\times10^{-3}W\pm0.002 \qquad r=0.78$$

$$\sigma_u^2 = 0.005+0.78\times10^{-3}W\pm0.002 \qquad r=0.70$$

$$\sigma_c^2+\sigma_u^2 = 0.008+1.56\times10^{-3}W\pm0.004 \qquad r=0.77$$

The (±) values give the standard deviations of the observed values from the corresponding values computed according to the regression lines. In computing the regression lines, each point is weighted according to the total number of densitometer readings on which it is based.††

6.4. Skewness and Peakedness

The determination of the skewness coefficients c_{21},c_{03} depends critically on the alignment of the grid and photograph. The data show a rather large scatter, but apparently the magnitude of coefficients increases with increasing wind speed for uncontaminated water. The regression lines are

$$c_{21}=0.01-0.0086W\pm0.03$$

and

$$c_{03}=0.04-0.033W\pm0.12.$$

In the presence of slicks the scatter of points is too great to evaluate the dependence on wind speed, if any. The weighted mean values are

$$c_{21}=0.00\pm0.02 \quad \text{and} \quad c_{03}=0.02\pm0.05.$$

Within the accuracy of the measurements, the peakedness coefficients are independent of wind speed

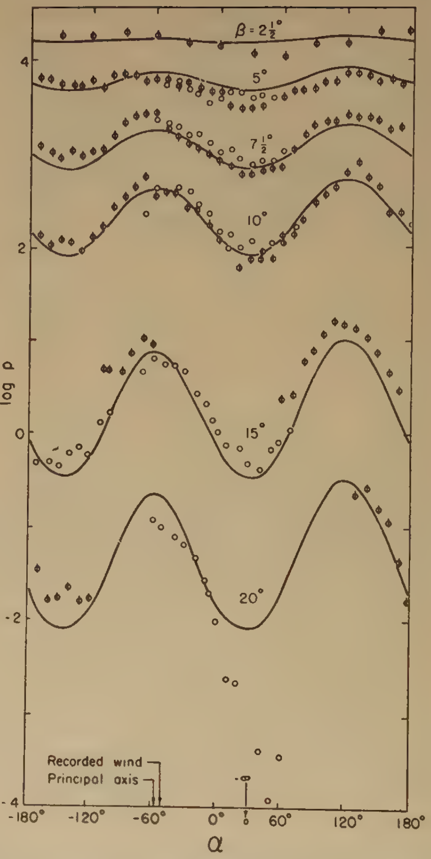

FIG. 7. Logarithm of unnormalized probability p as a function of azimuth α relative to sun, for indicated values of slope angle β. Open circles indicate data from tilted camera; barred circles, vertical camera. All measurements from photographs 4 Sept. k. Curves are drawn according to the Gram Charlier representation, Eq. (18). The position of the principal (y') axis is indicated relative to recorded wind direction.

** For nine photographic sets, 3 Sept. t; 4 Sept. y; 6 Sept. c; 10 Sept. k; 10 Sept. m; 10 Sept. r; 11 Sept. e; 11 Sept. f; and 13 Sept. e, the data showed no pronounced anisotropy. For these photographs the principal axes were arbitrarily taken in the direction of the wind and crosswind.

†† One point at $\sigma_c^2=0.0152$, $\sigma_u^2=0.0153$, $W=0.89$ m sec^{-1} (3 Sept t) was omitted in the calculation. The deviation of the $\sigma_c^2+\sigma_u^2$ value from the regression line is six times the standard deviation. Clearly some special conditions must apply to this observation. An examination of the wind record on 3 Sept. reveals that the wind was quite variable at the place where this observation was taken and was as high as 4.5 m sec^{-1} only 10 minutes before the photographs were taken. Quite possibly the wind speed at the vessel, which was just outside the glitter, was markedly lower than within the glitter area itself.

TABLE I.

Photograph designation[a]	Time[b]	Location of cameras N Lat	Location of cameras W Long	Location of cameras h (ft)[c]	Position of sun Altitude	Position of sun Azimuth	Wind Speed (ms⁻¹) 41 ft[c]	Wind Speed (ms⁻¹) 9 ft[c]	Wind Direction (true)	Sea surface	x +sun az[d]	Mean square slope components σ_c^2	Mean square slope components σ_u^2	Weight factor[e]
28 Aug *b*	1106	21°01.8′	156°45.8′	900	67°20′	119°	11.6	9.6	060°	clean	063°	0.0211	0.0390	125
28 Aug *p*	1336	20°59.0′	156°44.0′	2000	70°10′	236°	13.3	11.0	050°	clean	057°	0.0294	0.0484	155
28 Aug *u*	1403	20°58.2′	156°43.3′	2000	64°30′	246°	13.8	11.6	050°	clean	036°	0.0287	0.0452	157
28 Aug *v*	1403	20°58.2′	156°43.3′	2000	64°30′	246°	13.7	11.5	050°	clean	047°	0.0276	0.0404	160
3 Sept *j*	1157	20°39.5′	156°46.6′	2000	75°10′	150°	0.72	0.45	050°	clean	095°	0.00337	0.00489	114
3 Sept *q*	1330	20°39.5′	156°46.6′	2000	69°50′	230°	8.58	7.11	120°	clean	140°	0.0224	0.0230	158
3 Sept *t*	1357	20°39.5′	156°46.6′	2140	64°30′	242°	0.89	0.54	180°	clean	[g]	0.0152	0.0153	181
4 Sept *e*	1126	20°40.2′	156°40.3′	2000	70°10′	131°	1.79	0.49	045°	Nat. slick	120°	0.00096	0.00126	84
4 Sept *k*	1158	20°39.0′	156°40.0′	1950	75°00′	152°	3.93	3.58	100°	clean	94°	0.00694	0.00977	179
4 Sept *n*	1257	20°39.5′	156°36.9′	2000	74°30′	209°	8.00	6.62	100°	clean	126°	0.0136	0.0191	182
4 Sept *r*	1324	20°40.0′	156°39.3′	2000	70°30′	228°	6.30	5.27	111°	clean	136°	0.0134	0.0170	136
4 Sept *v*	1327	20°40.0′	156°39.3′	1000	70°00′	230°	6.44	5.4	111°	clean	119°	0.0136	0.0186	137
4 Sept *y*	1353	20°39.5′	156°36.9′	1900	65°00′	241°	4.92	4.07	110°	clean	[g]	0.0172	0.0174	139
5 Sept *b*	1058	20°40.5′	156°35.7′	1950	64°50′	121°	1.83	1.43	280°	clean	296°	0.00534	0.00906	156
5 Sept *g*	1124	20°40.1′	156°35.4′	1950	70°00′	131°	1.39	0.58	280°	clean	280°	0.00609	0.00875	156
5 Sept *j*	1354	20°46.8′	156°40.3′	2050	64°30′	240°	3.35	2.99	225°	clean	237°	0.0102	0.0125	188
6 Sept *c*	1048	20°58.5′	156°45.3′	1000	62°40′	120°	10.8	9.12	045°	clean	[g]	0.0252	0.0265	42
										oil slick		0.0111	0.0108	73
6 Sept *k*	1124	20°58.0′	156°44.5′	2000	69°10′	135°	10.2	8.85	045°	clean	040°	0.0254	0.0357	159
6 Sept *q*	1237	20°57.5′	156°44.0′	2000	75°20′	195°	11.7	9.92	045°	clean	045°	0.0254	0.0374	151
10 Sept *k*	1328	20°40.0′	156°38.3′	1800	67°50′	225°	8.45	7.24	130°	oil slick		0.0102	0.0117	97
10 Sept *m*	1333	20°40.0′	156°38.3′	900	67°00′	228°	7.15	6.00	130°	oil slick	[g]	0.00860	0.0100	100
10 Sept *r*	1347	20°39.7′	156°39.3′	2000	64°20′	232°	5.32	4.47	120°	clean	[g]	0.0137	0.0179	59
										oil slick		0.00967	0.00985	67
11 Sept *e*	1317	20°45.5′	156°41.8′	1000	69°20′	220°	5.45	3.75	210°	clean	[g]	0.0136	0.0137	137
11 Sept *f*	1317	20°45.5′	156°41.8′	1000	69°20′	220°	5.45	3.75	210°	oil slick	[g]	0.0107	0.0109	108
13 Sept *e*	1308	20°17.6′	156°02.4′	2150	69°50′	215°	2.41	1.97	090°	oil slick		0.00391	0.00467	86
13 Sept *f*	1308	20°17.6′	156°02.4′	2150	69°50′	216°	2.41	1.97	090°	oil slick	076°	0.00724	0.00959	136
17 Sept *e*	1136	20°29.9′	156°24.8′	2000	68°40′	149°	9.79	8.31	086°[h]	clean	080°	0.0209	0.0264	79
										oil slick		0.0106	0.0126	45
17 Sept *c, h, k, n, q*[f]	1111 1205	20°28′	156°24′	2000	65°15′ 71°30′	136° 169°	9.74	8.18	088°[h]	clean	087°	0.0230	0.0322	752
17 Sept *A*	1424	20°17.6′	156°14.8′	1800	54°40′	243°	10.5	8.45	068°[h]	clean	069°	0.0224	0.0365	172

[a] Includes date of observation, 1951.
[b] Time meridian 150°W.
[c] Elevation above sea level.
[d] True azimuth of principal (y') axis.
[e] Number of densitometer readings contributing to probability distribution.
[f] Probability distribution derived from 5 photographic sets.
[g] Observed wind direction used.
[h] Wind direction estimated from direction of wind streaks on water; recorded wind direction appears to be in error by twice magnetic variation.

and have the values

clean surface:

$c_{40}=0.40\pm0.23 \quad c_{22}=0.12\pm0.06 \quad c_{04}=0.23\pm0.41$

slick surface:

$0.36\pm0.24 \quad 0.10\pm0.05 \quad 0.26\pm0.31$

For details of the fitting procedure which lead to these values for the skewness and peakedness coefficients, as well as a tabulation of individual values of the probability index coefficients, we refer the interested reader to reference 7.

7. ESTIMATE OF ERRORS

In the preceding section we have included the standard deviations of the individual observation *from* the regression lines (for the mean square slopes and skewness) or *from* the mean values (for peakedness). The standard deviation *of* the mean peakedness is $n^{-\frac{1}{2}}$ times this value, where n is the number of observations. In addition, there are some systematic errors which do not show up in the scatter. A minor source of systematic error results from certain mathematical approximations in Sec. 6. These affect only skewness and peakedness.

Random Errors

Imperfections in the developing of the films result in errors in the photographic γ and these cause roughly proportional errors in the mean square slopes. They amount to about ± five percent. A more important source of error arises in the subtraction of background light. It will be recalled that the sky intensity curves were fitted to the reflected light just outside the glitter pattern (Sec. 5.3). This fitting is critically affected by the low intensity "toe" of the *D*-log*E* calibration of the photographic film and also by cloud reflections and other unknown factors. This is probably the principal cause of the scatter in peakedness. Variation in wind speed may also introduce scatter. Imperfect control for roll, pitch, and yaw by a fraction of a degree will introduce an error in skewness of the order of the scatter in skewness. In cases where the glitter is partly in a slick and partly out of a slick, the principal source of error in the skewness results from an imperfect separation of the data into these two categories.

Shadows and Multiple Reflections

Cloud shadows can be allowed for to some extent from a study of the image photographs.

Two complicating circumstances which have not been considered are (1) the presence of steep valleys in the sea surface which are hidden from the direct view of the camera,[10] or from the rays of the sun, and (2) the occurrence of multiple reflections. By neglecting these complications we introduce errors into any computation involving slopes steeper than one-half the elevation of the sun. We have largely avoided such errors by confining our measurements to sun elevations above 55°.

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[10] This accounts for the fact that one rarely sees distant trees, dunes, or ships reflected in the sea. The reason, as pointed out by Minnaert [M. Minnaert, *Light and Colour in the Upper Air*

Whitecaps

At high wind speeds the problem of whitecaps requires special consideration. We have located the whitecaps on the image photographs, and have omitted the corresponding dark spots on the photometric photographs from our measurements. At high winds this is troublesome, and we are likely to overestimate the frequency of high slopes. For some purposes it may have been more useful to determine the slope distribution regardless of whether such slopes are or are not related to whitecaps. Our method is not capable of doing this because of multiple reflection of light from foam bubbles.

Skylight

The major source of systematic errors results from the assumption of a uniformly bright sky dome in the background correction (Sec. 5.1). Without a further study of the variation in skylight it is impossible to estimate errors arising from this assumption. For high sun it seems reasonable that any deviations from uniformity depend largely on angular distance from the sun. In this case the resulting errors in mean square slope and skewness are small, but it is not impossible that this systematic error may be largely responsible for the calculated values of peakedness.

8. DISCUSSION AND SUMMARY

The Gram Charlier distribution function (18) gives an adequate description of the measured probability density p of the slope components up to two and one-half times their rms value. There is no information on larger (and more infrequent) slopes because of the limitations imposed by background radiation. With $m=\tan\beta$ designating the slope regardless of direction, and α' the angle of ascent measured to the right of the wind, it follows that

$$p\,dz_x'dz_y', \quad mp\,d\alpha'dm, \quad \text{and} \quad p\tan\beta\sec^2\beta\,d\alpha'd\beta$$

are the probability densities of slope within the limits

$$z_x'+\tfrac{1}{2}dz_x', \quad z_y'\pm\tfrac{1}{2}dz_y'; \quad \alpha'\pm\tfrac{1}{2}d\alpha', \quad m\pm\tfrac{1}{2}dm;$$

and

$$\alpha'\pm\tfrac{1}{2}d\alpha', \quad \beta\pm\tfrac{1}{2}d\beta,$$

respectively.

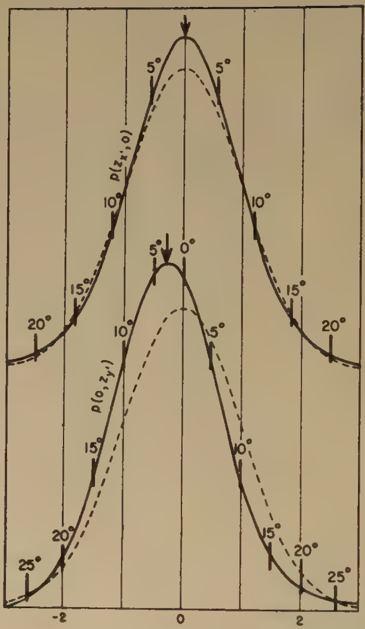

FIG. 8. Principal sections through the probability distribution surface $p(z_x',z_y')$. The upper curves are along the crosswind axis x'; the lower curves along the upwind axis y'. The solid curves refer to the observed distribution, the dashed to a Gaussian distribution of equal mean square slope components. The thin vertical lines show the scale for the standardized slope components $\xi=z_x'/\sigma_c$ and $\eta=z_y'/\sigma_u$. The heavy vertical segments show the corresponding tilts $\beta=5°, 10°, \cdots, 25°$ for a wind speed of 10 m sec^{-1}; the skewness shown in the lower curve is computed for this wind speed. The modes are marked by arrows.

The distribution function p is illustrated in Fig. 8. The mean square slope regardless of direction, $\sigma_c^2+\sigma_u^2$, increases linearly with wind speed, reaching a value of $(\tan 15.9°)^2$ for a wind speed of 14 m sec^{-1} measured at 41 ft elevation. The crosswind component σ_c^2 and up/downwind component σ_u^2 each increase linearly with wind speed, but the correlation is poorer because the variability in wind direction affects them separately but not their sum.

The principal axes are found to be oriented with the wind. The up/downwind mean square slope components are somewhat larger than the crosswind components. The ratio σ_u^2/σ_c^2 varies from 1.0 to 1.8 with a mean value of 1.34 for all photographs. For the slick surface the mean value is 1.16. This large variability is far in excess of experimental error. It is probably the result of differences, from one case to the next, in the *variability* of the wind direction. Steady winds would lead to large values in σ_u^2/σ_c^2 whereas gusty winds would diminish this ratio to somewhere near unity.

The skewness coefficients c_{21} and c_{03} of the Gram Charlier series decrease with increasing wind speed

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(G. Bell and Sons, London, 1940)], is that "at a great distance one sees only the sides of waves turned toward us. This makes it seem as if we saw all the objects . . . reflected in a slanting mirror." For the same reason, the reflection of low, distant clouds is displaced toward the horizon.

from nearly zero at very low winds to $c_{21}=-0.11$, $c_{03}=-0.42$ at 14 m sec^{-1}. At the higher wind speeds the most probable azimuth of ascent for low slopes is directed downwind, whereas for very large slopes ($|\eta|>3$) it is directed upwind. The principal source of error results from imperfect correction for the roll, pitch, and yaw of the plane. The peakedness coefficients c_{40},c_{22},c_{04} are such as to make the very large and very small slopes more probable than for a Gaussian distribution.

The effect of oil slicks covering an area of roughly one-fourth square mile is to reduce the mean square slope (regardless of direction) by a factor of two to three, to eliminate skewness, but to leave peakedness unchanged.

It is not difficult to show that gustiness leading to a standard deviation in wind speed of about one-third the mean wind speed could be responsible for the observed peakedness; nor is it impossible that systematic errors in the correction for background light may account for an appreciable part of the observed peakedness.

Comparison with Duntley

Duntley[11] has measured the surface slope components on Lake Winnipesaukee, N. H., by recording electrically the difference in immersion of pairs of thin vertical wires passing through the water surface. The wires were oriented to give simultaneous measurements of up/downwind and crosswind components. The separation between the wires was on different occasions 25 mm and 9 mm, consequently the measurements refer to the average value of slope over these distances.

Comparison of Duntley's results with ours show that (1) both investigations are consistent with a nearly Gaussian distribution of slopes; (2) both investigations indicate a linear increase of the mean square slope with wind speed; (3) the average value for the ratio σ_u^2/σ_c^2 is 1.5 for Duntley and 1.3 in our investigation; (4) the actual values for the mean square slopes are larger by a factor of 2.5 in Duntley's measurements than in ours. Possible explanations of (4) are the generation of short ripples by the wires themselves (fish line problem) as a consequence of the orbital movement of water past the wires and reflection of waves by the wire support mechanism.

Comparison with Schooley

Schooley's method[12] consisted of measuring the high-lighted area on *resolved* photographs of the reflection of an artificial light source over a river. At medium wind speeds the agreement of the two sets of data is satisfactory, although the ratio σ_u^2/σ_c^2 is somewhat higher in Schooley's data. For the highest and lowest wind speeds, Schooley's slope values are significantly smaller than ours.

The larger ratio σ_u^2/σ_c^2 may well be the result of a smaller variability of wind direction. Schooley's photographs were made from a bridge over the Anacostia River, consequently the glitter pattern covered a very much smaller area in his photographs than in ours, and correspondingly would be expected to sample a smaller variability in wind.

The low values of the mean square slope components at very low winds in the river may easily be due to contamination of the river surface. At moderate winds, surface films would be swept away. Schooley's low values at high winds may be due to (1) the fetch on the river being so short that the mean square slope was still increasing downwind, and (2) the imperfect resolution of high-lighted areas on Schooley's photos. Visual inspection of sun-glitter indicates that the curvature distribution of the sea surface becomes peaked at greater and greater values the higher the wind speed. This results in the glitter spots becoming smaller at higher winds. Resolution of the photographic setup then sets a limit to the wind speed for which highlights can be resolved.

ACKNOWLEDGMENTS

We should like to express our appreciation to Captain Michael Sbarra, USAF, and his officers and crew, and to Steacy Hicks and Robert Huffer and the crew aboard the *Reverie* for their spirit of cooperation during all phases of this investigation. In Monterey, the Air Force plane was stationed at the Naval Auxiliary Air Station and the *Reverie* docked at the USCG Life Guard Station. We are indebted to both activities for their excellent cooperation. In Hawaii Mr. William Neilson of the Hawaii Aeronautic Commission was most helpful in arranging facilities for the plane. Here facilities for calibrating and processing the films were quickly set up in an abandoned hangar by Chief W. L. MacDonald, USN, and T/Sgt V. R. Cooke, USAF, who had joined the operation at NAAS, Monterey, and Hickam AF Base, Hawaii, respectively.

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[11] S. Q. Duntley, "The visibility of submerged objects." Part I, Optical Effects of Water Waves. Mass. Inst. Tech. Report, Dec. 15, 1950, on U. S. Office of Naval Research Report NO N5 ori-07831.

[12] A. H. Schooley, J. Opt. Soc. Am. 44, 37 (1954).

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CARNEGIE RIDGE AND COCOS RIDGE IN THE EAST EQUATORIAL PACIFIC[1]

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ABSTRACT

Recently obtained sounding lines have been combined with published Hydrographic Office soundings to show the generalized bathymetry in the east equatorial Pacific. Carnegie Ridge is a relatively shoal area west of Ecuador, of which approximately 10,000 square miles lie shoaler than 1,000 fathoms and the shoalest portion is within 750 fathoms of the surface. The shallow northern extension of the Peru Trench bathymetrically separates Carnegie Ridge from the continental terrace. Cocos Ridge is a submarine ridge which extends southwestward from Costa Rica to the northern part of the Galapagos Islands. A relatively shoal zone of irregular topography is present for at least 560 miles west of the islands. Between Costa Rica and the Galapagos Islands the general depth along the ridge is between 900 and 1,000 fathoms; but irregularities project to lesser depths, and one of these forms volcanic Cocos Island. Four echograms taken across the ridge failed to reveal truncated seamounts upon it.

On the basis of the bathymetry of Carnegie Ridge and the geological history of Colombia and Ecuador, it is speculated that the easternmost portion of Carnegie Ridge may once have been part of the western borderland for the early Tertiary geosyncline which existed along the present coastal lowlands of western Ecuador. This would have shortened the sea route to the Galapagos Islands and possibly facilitated the rafting of plants and animals to the Islands. A recently proposed explanation for the origin of Galapagan life called for the emergence of Cocos Ridge to within a short distance of the Islands in Miocene time, but the apparent absence of truncated seamounts on Cocos Ridge is evidence against a former emergence. The portion of Cocos Ridge lying west of the Galapagos Islands resembles, in trend and topography, the four great submarine fracture zones which are found west of North America.

INTRODUCTION

SOURCES OF INFORMATION

Recent expeditions of the Scripps Institution of Oceanography and the U.S. Navy Electronics Laboratory have obtained new bathymetric data in the east equatorial Pacific (fig. 1). The expeditions were "Shuttle" and "Shellback," made in 1952, and "Capricorn" of 1952–1953. These data, together with soundings from the U.S. Navy "Expedition Hijump" of 1946–1947 and from Hydrographic Office charts, make it possible to discuss two areas of interesting submarine topography which previously have been little known.

The Shuttle Expedition was made on the U.S. Navy Electronics Laboratory ship "EPCE(R)857"; the Shellback Expedition was made on the research vessel "Horizon." Capricorn involved two research vessels of the Scripps Institution, the "Horizon" and the "Spencer F. Baird."

PURPOSE OF THE INVESTIGATION

Shellback, Shuttle, and Capricorn were essentially reconnaissance expeditions intended to determine broad oceanographic conditions in the Pacific Ocean through the use of present-day instruments. The results of such expeditions form a framework of knowledge which is essential for the planning of future studies of a more detailed nature. This paper is a synthesis of presently available, essentially reconnaissance, data showing the general pattern of bathymetry in the easternmost equatorial Pacific.

The geological significance of the ocean-floor features discussed in this paper are mentioned as speculations for the most part, because there is practically

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[1] Contribution from the Scripps Institution of Oceanography, New Ser., No. 738. Manuscript received September 23, 1953.

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no geologic information other than bathymetry presently available.

CARNEGIE RIDGE

INTRODUCTION

Carnegie Ridge is a relatively shoal sea-floor area west of Ecuador, which is separated bathymetrically from the continental shelf by the northern extension of the Peru Trench (fig. 2). This feature was discovered during the last cruise of the research vessel "Carnegie," in 1928 (Paul, 1932, p. 153). Sounding lines obtained in recent years make it possible to present a contoured chart of the area (fig. 3) and bathymetric cross sections.

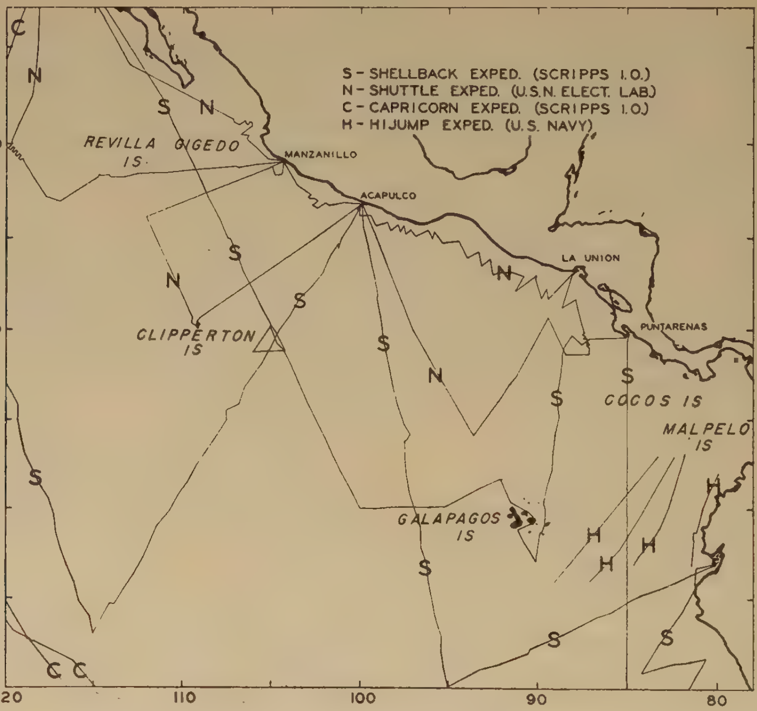
S - SHELLBACK EXPED. (SCRIPPS I.O.)
N - SHUTTLE EXPED. (U.S.N. ELECT. LAB.)
C - CAPRICORN EXPED. (SCRIPPS I.O.)
H - HIJUMP EXPED. (U.S. NAVY)
REVILLA GIGEDO IS
MANZANILLO
ACAPULCO
LA UNION
PUNTARENAS
CLIPPERTON IS
COCOS IS
MALPELO IS
GALAPAGOS IS
S
N
C
H
20
10
0
10
120
110
100
90
80

FIG. 1.—East Pacific sounding lines, 1946–1953

In November, 1928, the research vessel "Carnegie" proceeded southward from Panama, making hydrographic and bottom-sampling stations off Colombia and Ecuador. At each station a sor depth determination was made, partly prevent delicate instruments from bei lowered onto the bottom by mistake. station 40, about 100 miles off the coa of Ecuador (fig. 3), the echo sounder w out of order, but sampling gear was se down anyway, on the assumption th the 3,300-meter depth given by the ava able chart was reasonable. Bottom w found at half this depth, and a pian wire sounding gave a depth of 1,4 meters (795 fathoms) (Paul, 1932). A parently Carnegie Ridge was named the basis of this single sounding, for t next "Carnegie" station at which botte samples and a depth determination we made is located west of the Galapag Islands.

The bottom-sediment sample obtain

on "Carnegie" station 40 consists "principally of angular fragments of altered volcanic material and iron concretions greater than 0.5 and less than 8 mm. in diameter, partly encrusted with worm tubes, together with a few pelagic Foraminifera, sponge spicules, wood fibers, but no mud" (Revelle, 1944, p. 18).

BATHYMETRY

Hydrographic Office Charts 0823 and 1177 give a number of soundings in the Carnegie Ridge area, but these alone are too scattered to allow reasonable contouring. Four lines of soundings across the area were taken by ships engaged in the Hijump Expedition. The research vessel "Horizon" obtained a continuous echogram along the 85th meridian, midway between the Galapagos Islands and Ecuador during the Shellback Expedition.

A contoured chart of Carnegie Ridge prepared from these soundings (fig. 3) shows the area to be roughly triangular in shape and to merge in a westerly direction with the raised sea floor which extends eastward from the Galapagos Islands. A trench bounds the area on the east. For purposes of discussion the western boundary of Carnegie Ridge will be considered as the 85°30′ W. meridian, be-

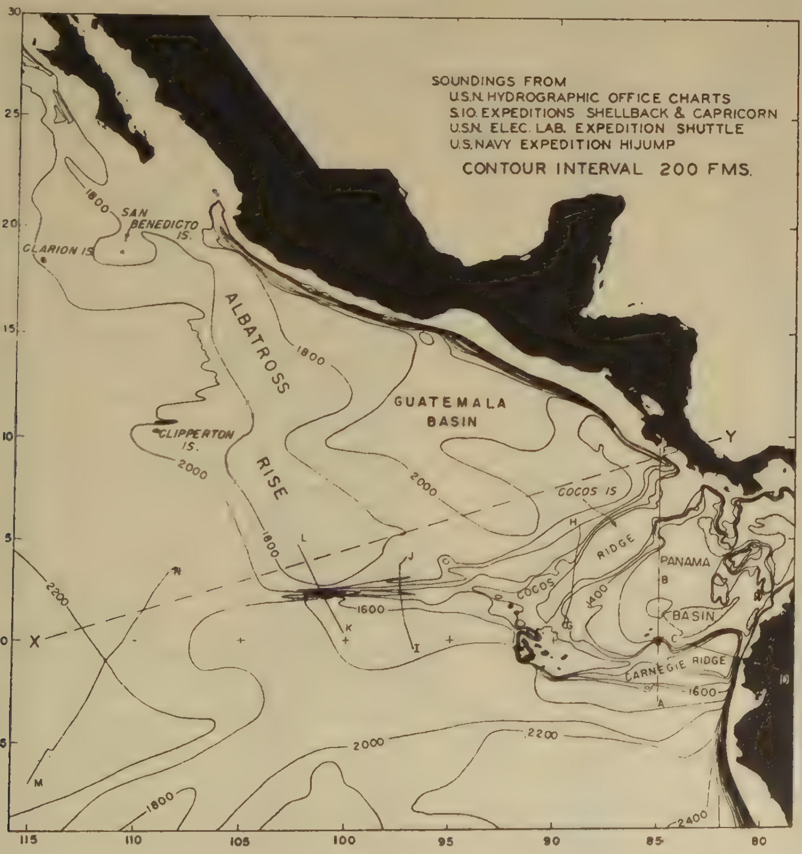
SOUNDINGS FROM
U.S.N. HYDROGRAPHIC OFFICE CHARTS
S.I.O. EXPEDITIONS SHELLBACK & CAPRICORN
U.S.N. ELEC. LAB. EXPEDITION SHUTTLE
U.S. NAVY EXPEDITION HIJUMP
CONTOUR INTERVAL 200 FMS.
SAN BENEDICTO IS.
CLARION IS.
ALBATROSS RISE
CLIPPERTON IS.
GUATEMALA BASIN
COCOS IS
COCOS RIDGE
PANAMA BASIN
CARNEGIE RIDGE
X
Y
A
B
C
G
H
I
J
K
L
M
N
1800
2000
2200
1600
1400
2400
30
25
20
15
10
5
0
5
115
110
105
100
95
90
85
80

FIG. 2.—Generalized bathymetric chart of east equatorial Pacific. North of line *X–Y*, contours below 1,800 fathoms only; south of *X–Y* contours below 1,000 fathoms only. Seamounts are not indicated.

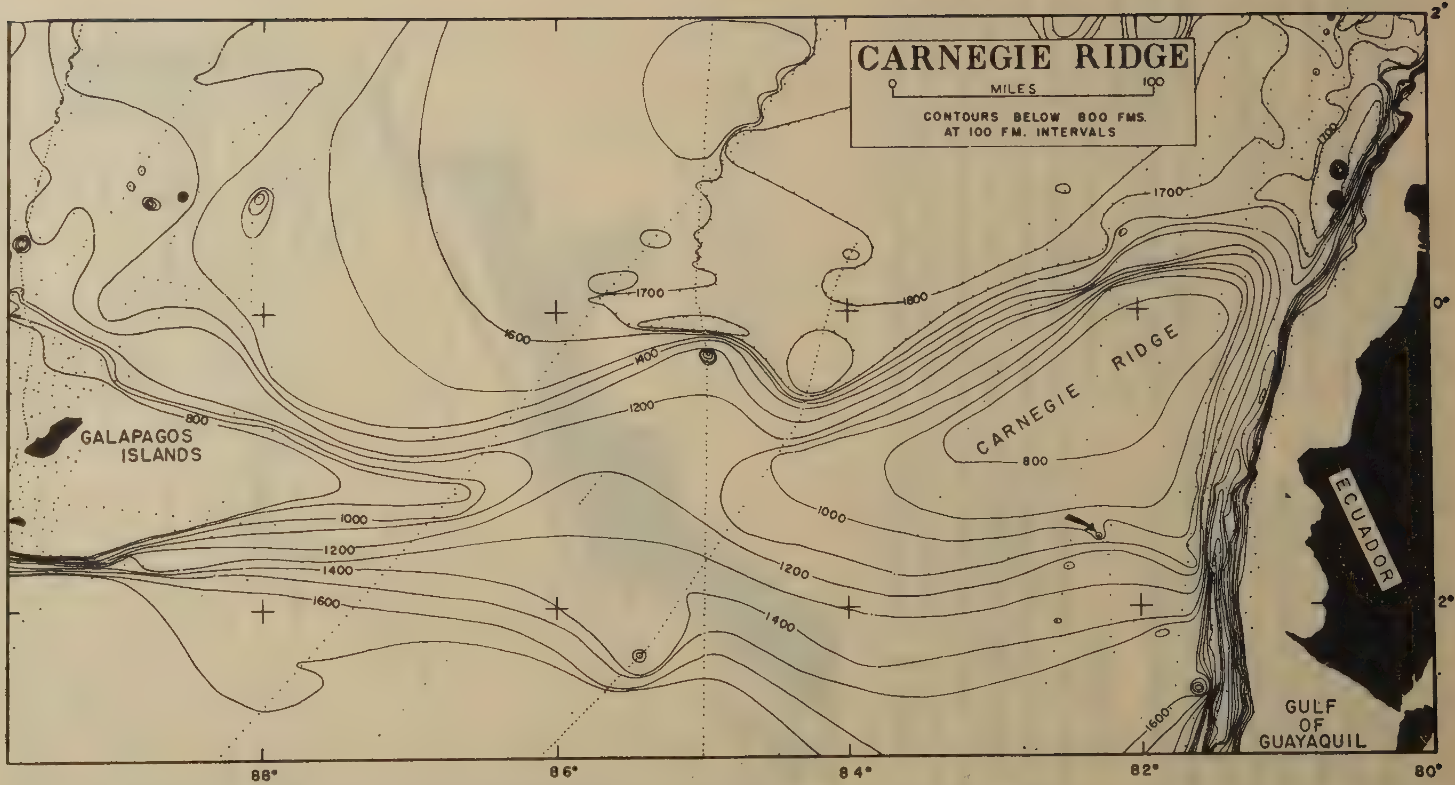
CARNEGIE RIDGE
MILES
0
100
CONTOURS BELOW 800 FMS.
AT 100 FM. INTERVALS
CARNEGIE RIDGE
GALAPAGOS ISLANDS
ECUADOR
GULF OF GUAYAQUIL
800
1000
1200
1400
1600
1700
1800
88°
86°
84°
82°
80°
2°
0°
2°

Fig. 3.—Bathymetric chart of Carnegie Ridge. The shoalest part of Carnegie Ridge lies deeper than 700 fathoms; so only contours below 800 fathoms are shown. Original "Carnegie" sounding is indicated by arrow.

cause the roughly triangular Carnegie Ridge area meets the relatively shoal area east of the Galapagos Islands at about this longitude.

The existence of a trench off Peru (Schweigger, 1947) and Chile (Monaco charts) is well known. The presence of a trench at the eastern end of Carnegie Ridge establishes the fact that a trench is present along the west coast of South America more or less continuously from Colombia to Chile. Schweigger assumed that north of Peru the feature lost significance because the trench axis shoals considerably. The axis does rise to the north off northern Peru and southern Ecuador, but the sea floor on the oceanic side of the trench rises concomitantly to form Carnegie Ridge; so the trench persists as a prominent bathymetric feature. East of Carnegie Ridge the trench attains a depth between 1,400 and 1,500 fathoms at the equator (fig. 3). The axis deepens north of the equator, and depths greater than 2,000 fathoms occur off Colombia and Ecuador.

Central and South America, Carnegie Ridge, the Galapagos Islands area, and Cocos Ridge enclose a basin. Jones (1950, p. 912) considered that the relatively shoal area in the vicinity of Malpelo Island subdivided the basin into the Galapagos–Panama Basin to the west and the Ecuador Basin to the east. A number of sub-basins probably are present within the large basin, and in this paper the term "Panama Basin" is used in reference to the large feature as defined above.

The "Horizon" sounding line and echogram, obtained during a north-south crossing of Carnegie Ridge (*A–B* in figs. 2 and 4), shows that the sea floor rises gently from south to north in forming the southern slope of the ridge. The north side of Carnegie Ridge at this location is a scarp 600 fathoms in height which has

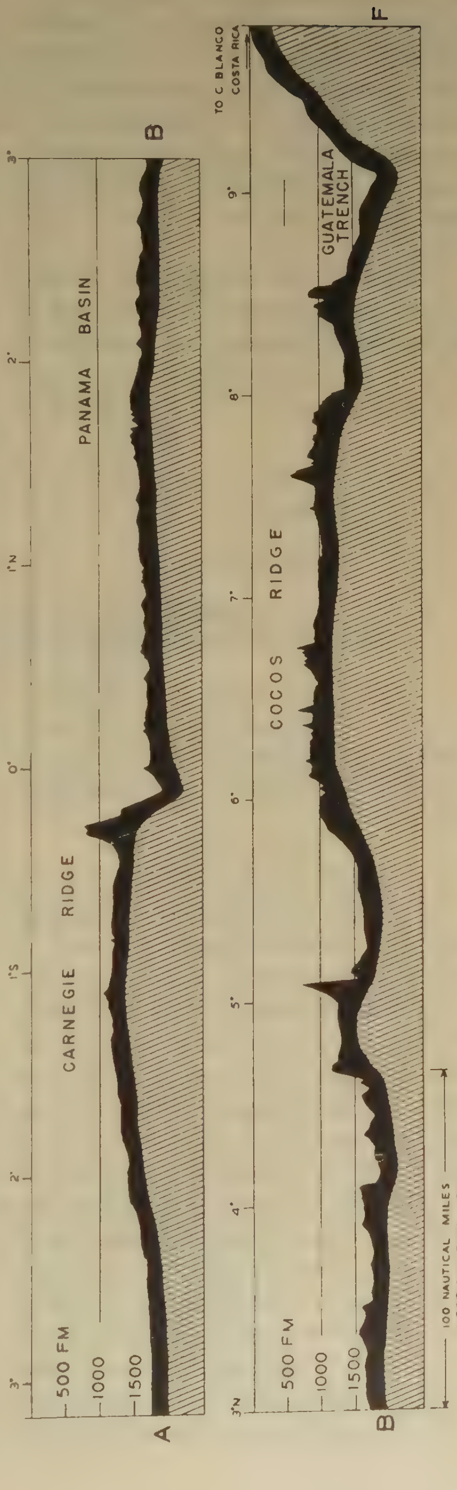

Fig. 4.—Profile crossing Carnegie Ridge, Panama Basin, Cocos Ridge along 85th meridian. See fig. 2 for location

either a seamount or a ridge perched on top of it. The soundings from Expedition Hijump do not include a lateral extension of the scarp, but they are relatively far from the "Horizon" line along the north slope. Most of the raised area, as represented by the "Horizon" crossing, has topographic variations of less than 100 fathoms.

To illustrate the relationship of relief between the submarine topography in the Carnegie Ridge area and the adjacent subaerial topography of Ecuador, a profile was prepared (fig. 5) approximately perpendicular to the trench (*C–D* in fig. 2). Bathymetric data were taken from figure 3.

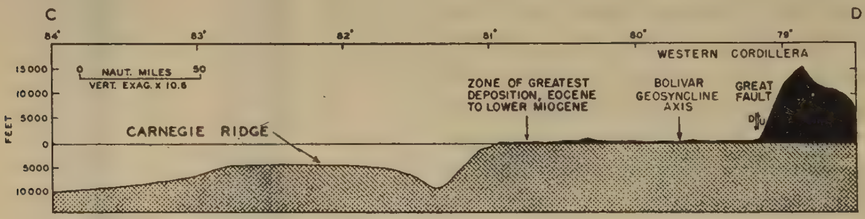

FIG. 5.—Profile across Carnegie Ridge, trench, western Ecuador. See fig. 2 for location

GEOLOGICAL SIGNIFICANCE

The geological significance of Carnegie Ridge is at present largely a matter of speculation, because the available bathymetric data are unsupported by bottom sampling and geophysical measurements. The bathymetric relationship of the area to the South American continent suggests that possibly it has had a part to play in the geological development of Colombia and Ecuador. In discussing the structural evolution of the South American Andes, Oppenheim (1947) concludes that there is no good evidence calling for the past existence of continental lands west of the present continental slopes; but he mentions that in Tertiary time minor continental extensions did exist west of Colombia and Ecuador, as is evidenced by the stratigraphic development of their coastal sediments. The easternmost portion of Carnegie Ridge lies close to the continent and possibly it may once have served as a Tertiary geosynclinal borderland.

During the Tertiary a well-developed geosyncline had its axis along the present coastal lowlands of Colombia and Ecuador (Nygren, 1950). In Ecuador the zone of greatest deposition from the Eocene to early Miocene lay to the west of the Bolivar geosyncline axis, which existed from middle Miocene to Recent (fig. 6). Nygren mentions that abundant easterly dipping sediments lie west of the Bolivar geosyncline axis, and he considered this to be an indication that Tertiary borderlands probably existed where the eastern portion of the Panama Basin is now located. Marine deposition in the Bolivar geosyncline was continuous from the Oligocene through the middle Miocene. According to Nygren, the western borderland was evidently a rather wide lowland area during the Miocene, for the geosynclinal deposits east of it consist of shales, marls, and limestones, with very little coarse material. Considerable tectonic activity occurred in Ecuador during and after the Tertiary, according to Sheppard (1930). He mentions that the early Tertiary deposits are much more disturbed than beds of Miocene age and younger.

The geological history of coastal Colombia and Ecuador thus suggests that a geosynclinal borderland may once have been present in the area of the easternmost part of Carnegie Ridge. The most likely time for its existence would have been the early Tertiary. The axis of greatest sediment accumulation in Ecuador from the Eocene through the early Miocene was the most western part of the present lowland region, which is the land nearest to Carnegie Ridge (figs. 5, 6). A period of increased orogenic activity, including faulting and volcanism, began in the late middle Miocene, and at this time the geosynclinal western borderland, except for a narrow strip, was foundered by downfaulting, and the eastern borderland was raised to become the western Cordillera (Nygren, 1950).

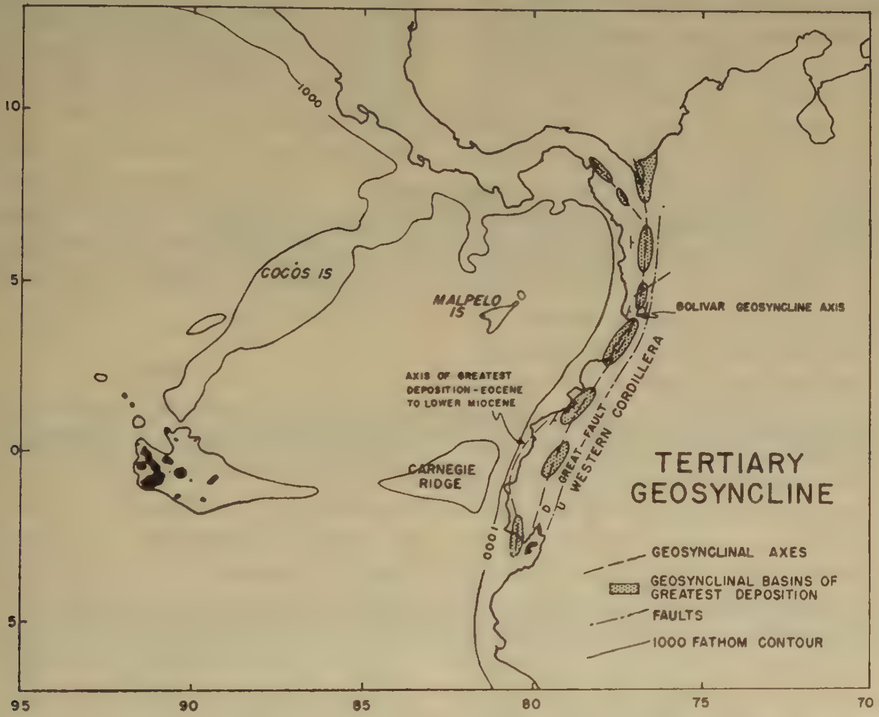
10
5
0
5
95
90
85
80
75
70
1000
COCOS IS
MALPELO IS
AXIS OF GREATEST DEPOSITION - EOCENE TO LOWER MIOCENE
CARNEGIE RIDGE
1000
BOLIVAR GEOSYNCLINE AXIS
GREAT FAULT
WESTERN CORDILLERA
TERTIARY GEOSYNCLINE
GEOSYNCLINAL AXES
GEOSYNCLINAL BASINS OF GREATEST DEPOSITION
FAULTS
1000 FATHOM CONTOUR

FIG. 6.—Tertiary geosynclines of Ecuador and Colombia. After Nygren (1950), with 1,000-fathom contour added to indicate Carnegie Ridge.

No attempt is made to explain the presence of a trench between Carnegie Ridge and the South American continent. Were it not present, the speculation that Carnegie Ridge is a foundered borderland area would be more reasonable. West of Peru a great trench parallels the Peruvian Andes for approximately 1,000 miles, and it has been suggested that the formation of the trench is related to the tectonic development of the mountains (Schweigger, 1947). In northwestern Peru and southern Ecuador the great north-northwest Peruvian mountain trend dies out. East of the Gulf of Guayaquil is a zone of poorly defined mountain trends at the junction of the Colombian-Ecuadorian Andes and the Peruvian Andes. West of this area a trench is present (the trench east of Carnegie Ridge). If the development of the Peru Trench is closely related to the uplift of the Andes, it is difficult to account for the northern extension of it west of an area where mountain trends are ill-defined and are not parallel to the coast.

The shoalest portion of the trench east of Carnegie Ridge probably is the controlling sill for the Panama Basin, provided that there are no gaps or bathymetric lows crossing Cocos Ridge at depths greater than the 1,400–1,500-fathom trench-axis depth. The small width of the trench may prevent it from being effective as a sill in the oceanographic sense, however. On the assumption that the sill depth was approximately 1,100 fathoms, Wooster (1952) compared the average temperature, dissolved oxygen, and dissolved silicate contents between 2,400 and 2,750 meters (1,320 and 1,500 fathoms) for a typical hydrographic station northwest of the basin, in it, and south of it. He found the temperature at least 0°2 C. higher within the basin than at either station northwest or south of it. The oxygen and silicate concentrations in the basin were more closely related to the station northwest of the basin, and Wooster concluded that the deep circulation may be toward the south and east, to be limited by the topographic saddle at the western end of Carnegie Ridge. This relationship was also shown for the dissolved phosphate concentrations (Wooster, personal communication). He considered that the replenishment of deep water in the basin is undoubtedly slow and that the slight increase in temperature there is due entirely to diffusive processes.

COCOS RIDGE

PREVIOUS KNOWLEDGE

Hydrographic Office Charts 5486, 0526, 0823, 1007, and 1798 contain shoal soundings along a zone which extend southwestward from Costa Rica towar the Galapagos Islands. The relativel shoal area surrounding the Galapagos Islands and including the Cocos Islan area was called the Galapagos Plateau b Agassiz (1906, pl. 2), but his bathymetri chart of the eastern Pacific does not sho that the shoal zone extends to Cost Rica. Jones (1950) indicated the genera plan of this topographic feature fro contours on H.O. Chart 5486 (issue 1939) and appropriately named it Coco Ridge because Cocos Island is presen along the ridge midway between th Galapagos Islands and the mainland Vinton (1951) also recognized that a submarine ridge extended southwestwar from Costa Rica.

BATHYMETRY

A relatively shoal area is present nort of the Galapagos Islands and extends fo at least 560 miles west of them (fig. 2) For purposes of discussion it is considered that this relatively shoal zone is western extension of Cocos Ridge an that the shoal area surrounding the Galapagos Islands, especially on the east, is separate area. Between the Galapago and Central America the ridge has a general depth between 900 and 1,000 fathoms, with irregularities projecting t lesser depths; its trend is northeas southwest. West of the Galapagos Islands the ridge has approximately a east-west trend. Seamounts are appa ently numerous along Cocos Ridge, bu few indeed have appeared on publishe charts. Tuna fishermen know the area one of many productive fishing bank but exact locations are retained as trac secrets. A pile of volcanic material pr jecting upward from the ridge form Cocos Island (Chubb, 1933). The She back Expedition obtained four contin ously recorded echograms across the ridge (fig. 2), and, on the basis of profiles constructed from these (figs. 4, 7), some comments may be made about the ridge.

A crossing of Cocos Ridge along the 85th meridian shows the ridge to lie at a general depth of 1,000 fathoms, with jagged irregularities projecting upward by as much as 400 fathoms (*B–F* in fig. 4). The Guatemala Trench is present north of the ridge at this location. It is not known from present data whether the trench terminates at Cocos Ridge or continues southeasterly, to separate the ridge from the Central American isthmus. H.O. Chart 1007 shows only a few soundings at the landward end of Cocos Ridge, and the deepest of these is 1,055 fathoms; so perhaps the trench ends at the ridge.

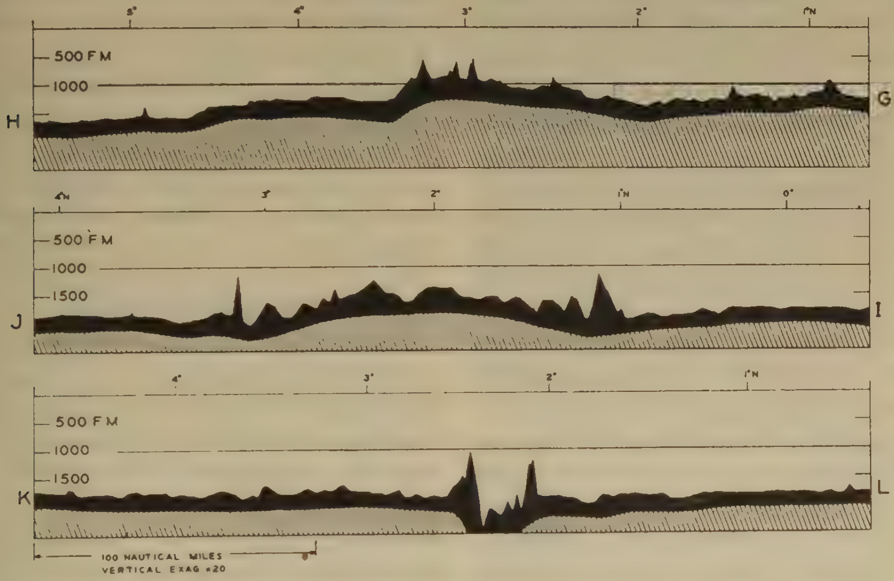

Fig. 7.—Profiles across Cocos Ridge. See fig. 2 for locations

A profile crossing Cocos Ridge between the 88th and 90th meridians shows that the highest part of the ridge lies at a general depth between 900 and 1,000 fathoms (*G–H* in fig. 7). Irregularities of 400-fathom relief project above the general level on this crossing also. On the north flank of the ridge a scarp is present, and below this the sea floor becomes deeper in a series of steps or terraces. These flat areas do not have the appearance of the terraces formed by sediment fill on the flanks of the Mid-Atlantic Ridge (Tolstoy, 1951, p. 445, pls. 5, 6) and are perhaps structural rather than depositional features. North of the ridge the sea floor below 1,500 fathoms slopes gently north at about 15 feet per nautical mile, with few irregularities. South of the ridge the sea floor has rugged topography, and depths are less than 1,500 fathoms.

West-northwest of the Galapagos Islands a 150-mile-wide zone of rugged topography indicates that Cocos Ridge does not terminate at the Galapagos but continues at least as far westward as the 97°30′ meridian (fig. 2; *I–J* in fig. 7). At this position the ridge lies deeper than at the two crossings farther east, but the relief is about the same—about 800 fathoms if the tops of the highest irregularities are considered; about 400 fathoms if the general level of the ridge is considered. Crossing *I–J* shows a marginal depression at either side of the ridge, with a sharp peak rising to less than 1,200 fathoms from each low area. Brief bathymetric surveys of these peaks established that they are conical seamounts.

The influence of Cocos Ridge persists as far west as the 101st meridian. Section *K–L* (figs. 2, 7) shows a 35-mile-wide zone of irregular topography with relatively smooth sea floor for at least 100 miles on either side of it. The irregular zone consists of two projections above the general 1,800-fathom level of the sea floor, with a 15-mile-wide zone between them which lies lower than 1,800 fathoms. A 1,400-fathom difference exists between the deepest and shoalest soundings of the crossing.

The bathymetric relationship between Cocos Ridge and the Galapagos Islands is not evident from the available data. The ridge is believed to pass north of the main island group (fig. 2), but more sounding lines are needed to show the actual situation. The two most northern islands in the Galapagos group—Culpepper Island and Wenman Island—appear to be bathymetrically separated from the main island group by a relatively deep area and may be more closely related to Cocos Ridge than to the main group of Galapagos Islands.

COCOS ISLAND

Cocos, a volcanic island roughly 3 by 5 miles in size, is composed chiefly of massive lava flows (Chubb, 1933). On the basis of rock analyses presented in Chubb's work, Macdonald (1949) presented a figure showing that the boundary of the Pacific Basin passes between Cocos Island and the Galapagos Islands, but he indicated that the evidence was scanty. The descriptions of the Cocos Island rocks were apparently only sufficient to suggest that the lavas were of continental nature. Macdonald considers that the Galapagos rocks are similar to those of the Hawaiian petrographic province, judging from Chubb's reports and from a rock obtained by the Shellback Expedition at Academy Bay on Santa Cruz Island, which Macdonald identified as an olivine basalt containing titanium-bearing pyroxene (personal communication).

Gutenberg (1941, 1951) mentions that all reflections of longitudinal seismic waves from under the ocean floor north and north-northeast of the Galapagos Islands indicate "Pacific" type crustal structure rather than continental type.

GEOLOGICAL SIGNIFICANCE

Cocos Ridge and the shoal area south of it which surrounds the Galapagos Islands include an area as large as Central America (fig. 2). The bathymetry of the area is complicated, and probably no simple tectonic process could account for it. For purposes of discussion three regions may be considered separately: the Galapagos Islands area, Cocos Ridge west-northwest of the Galapagos, and Cocos Ridge northeast of the Galapagos. It is possible that the bathymetry of each of these areas has developed somewhat independently.

Earthquakes with shallow epicenters have been reported in the vicinity of Cocos Ridge and the Galapagos Islands, but there appears to be no particular concentration of epicenters in these areas with respect to the surrounding sea floor (Gutenberg and Richter, 1949).

Galapagos Islands area.—Darwin (1844, p. 116–117) first called attention to the fact that the major craters of the

Galapagos seem to lie at the intersection of two sets of parallel lines which trend about N. 43° W. and N. 47° E. Chubb (1933) commented briefly upon the structure and geologic history of the Galapagos Islands, but few data have come from the area since his work; he considered that the southeastern part of the archipelago probably contained the oldest volcanos.

A comment may be made about the area on the basis of the generalized bathymetry (fig. 2) and on observations made during the Shellback Expedition (fig. 1). Southwest of the islands, a short distance from land, the sea floor drops to depths greater than 1,800 fathoms. South of the largest of the islands, Isabella, a depression is present at the base of the slope, and outside this zone the general depth is about 100 fathoms shoaler. This deep area is not well defined by the available soundings, and future investigations may show it to bear a relation to the Galapagos Islands somewhat comparable to that between the Hawaiian Islands and the Hawaiian Deep, which is found east and northeast of them (Dietz and Menard, 1953), or more simply to the marginal depressions occasionally found at the base of seamounts (Menard and Dietz, 1951).

Cocos Ridge west-northwest of the Galapagos Islands.—West of the 95th meridian Cocos Ridge is similar to the great submarine fracture zones which lie west of North America (Menard, 1953), if sounding lines *I–J* and *K–L* (fig. 7) are representative. The most westerly crossing of the ridge (*K–I*) revealed two peaks about 20 miles apart, which rise 500 or 600 fathoms above the general level of the surrounding sea floor. Between the peaks is a zone of irregular topography which lies 100 or 200 fathoms deeper than the general level. This type of feature is typical of the submarine fracture zones.

Examination of a continuous echogram obtained by Expedition Shellback along line *M–N* (figs. 1 and 2) revealed only a featureless sea floor for more than 750 miles, and it is therefore believed that the Cocos Ridge trend does not extend so far west as this line. It is possible, however, that the trend is present farther to the west than line *M–N*, because on Expedition Shellback a depression of 200 fathoms' relief, accompanied by a 50-fathom change in general sea-floor level, was crossed at about 1°28′ N., 118°5′ W.

The western portion of Cocos Ridge lies about 560 miles south of the Clipperton Island fracture zone described by Menard (1953). The great fracture zones which he describes have separations of either 600 or 1,200 miles, approximately; hence the western portion of Cocos Ridge lies a correct distance south of the Clipperton Island feature to be a fifth fracture zone.

Cocos Ridge northeast of the Galapagos Islands.—This portion of the ridge has a width at the 1,000-fathom isobath comparable with that of the Isthmus of Panama (fig. 2), and it has a relief which is similar to that of the uplands of Central America (*B–F* in fig. 4). It is tempting to think of it as a submarine isthmus-like feature. With this idea in mind, it has been suggested recently that the area once stood above sea-level as a peninsula extending nearly to the Galapagos Islands (Vinton, 1950). This hypothesis of past emergence was based on the need for an explanation for the origin of life on the Galapagos and will be discussed in the following section.

This portion of Cocos Ridge was mentioned by Vening Meinesz (1947) as topography which seemed to correlate with a shear pattern he had developed for the entire earth. Starting from the observed pattern of topographic trends in the Atlantic and Indian Oceans, he developed a theoretical shear net for the earth which would be in harmony with these features and which would correlate with a number of topographic trends elsewhere on the earth. His shear net was that which would be produced if the earth's pole had at some time in the remote past shifted 70° along the 90° E. meridian, to arrive at its present position. He mentioned that in the West Indies a close correlation between topography and the net is not found, but certain features of the area are in agreement with the net. One of these is the trend which begins as the eastern portion of Cocos Ridge and continues along the east coast of Nicaragua and which perhaps has a continuation along the continental shelf of the east coast of North America.

ORIGIN OF LIFE ON THE GALAPAGOS ISLANDS

Vinton (1951) reviewed the problem of explaining the origin of life on the Galapagos Islands and discussed the conclusions of a number of authors. As some of these writers point out, the floral and faunal assemblages on the islands are not of the diversified nature that would be expected, had the islands once been connected to Central America by a continuous land bridge. Vinton's conclusions call for a peninsula extending nearly to the islands but separated from them by water. The chance rafting of plants and creatures, along with flotsam and jetsam from the peninsula, would be the needed mechanism of transport. After a study of H.O. charts he suggested the possibility that Cocos Ridge once stood above sea-level from Costa Rica to within about 100 miles of the Galapagos Islands. This would have occurred during the Oligocene and Miocene. With the Isthmus of Panama breached in places by the ocean, the current system would perhaps have been favorable for the transportation of floating objects to the islands.

The Vinton hypothesis is perhaps the most reasonable one put forward to date, but unfortunately there is little supporting geological evidence for it. The presence of truncated seamounts along the ridge would be one of the best evidences of former emergence, but profiles *B–F* and *G–H* (fig. 7) do not show such features. Submerged flat-topped seamounts or guyots, are known in the central Pacific (Hess, 1946; Hamilton, 1952), the Gulf of Alaska (Menard and Dietz 1951), and west of southern Californi (Carsola and Dietz, 1952) and are considered to be the result of beveling at o near sea-level by wave erosion, followe by submergence. It is possible that som of the peaks of Cocos Ridge are similarl truncated, but as yet they have not bee found. It is also possible that some of th peaks indicated in the crossings represen only the sides of conical seamounts whic might have flat tops.

The presence of Carnegie Ridge between the Galapagos Islands and Ecuador suggested to the writer an alternativ hypothesis for explaining the migration of life to the islands. If the easternmos portion of Carnegie Ridge extende above sea-level at some appropriate tim in the past, then the sea route fro South America to the islands would b shortened to a few hundred miles. Th might have occurred during the earl Tertiary, as previously discussed. Th Peru Current, which probably existe during the Tertiary with a pattern n unlike that which we find today (Woo ter, 1952), would swing along the sout ern shore of the land mass and produce continual one-way passage to the islan for floating objects. According to Sim son (1943), the Galapagan tortoises have their closest affinities with tortoises of South America.

The Carnegie Ridge hypothesis is not intended to supersede the mechanism proposed by Vinton. From a marine geological point of view the two hypotheses have about equal merit and should both be considered possible until future work sheds light upon these ideas or brings forth new ones.

CONCLUSIONS

Darwin's accounts (1839, 1844) of his visit to the Galapagos Islands in 1835 introduced the problem of explaining both the origin of the islands and the origin of life on the islands; yet now, more than a hundred years later, we can hardly do more than speculate about them, as he did. Since Darwin's time a fairly broad understanding of the geological development of Central and South America has been gained. Most recently it has been realized that marine geological and geophysical studies can help to complete a story which land geology by itself cannot reveal. It is hoped that this paper will be useful as a guide for future geological studies in the east equatorial Pacific.

Certain areas may be mentioned as important for further investigation. Bathymetric bottom-sampling and geophysical studies of the eastern portion of Carnegie Ridge and the trench east of it would shed light on the speculation that the area was once part of a Tertiary geosynclinal borderland. The deep area at the base of the sea-floor slope south and west of Isabella Island of the Galapagos Island group should be bathymetrically and gravimetrically surveyed, because it may contain clues as to the nature of crustal structure in the vicinity of the Galapagos. The junction of Cocos Ridge with the continental terrace off Central America needs investigation, as does the portion of Cocos Ridge north and west of the Galapagos.

ACKNOWLEDGMENTS.—R. L. Fisher directed a bathymetric survey of the trenches off Mexico and Central America during the Shuttle Expedition (fig. 1), and he has kindly allowed his data to be used in the preparation of figure 2. H. W. Menard was investigating the great submarine fracture zones which are found west of North America (Menard, 1953) at the time that this work was being done, and his constructive criticism has been especially helpful. Appreciation is expressed to the following people for taking time to read and suggest improvements in the manuscript: R. L. Fisher, R. W. Raitt, and F. P. Shepard of the Scripps Institution of Oceanography.

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AT HARVARD COLLEGE
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THE COMPARATIVE BIOLOGY OF REPRODUCTION IN THE WOOD-BORING ISOPOD CRUSTACEAN *LIMNORIA*

By Robert J. Menzies

CAMBRIDGE, MASS., U. S. A.
PRINTED FOR THE MUSEUM
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No. 5 — *The Comparative Biology of Reproduction in the Wood-Boring Isopod Crustacean Limnoria*[1]

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CONTENTS

PAGE

Introduction 364

Materials and Methods 364

Comparative morphology of the reproductive organs ... 365
  Internal anatomy 366
    Female 366
    Male 367
  External anatomy 370

Sex determination 371
  Sex ratio 371
  Ambisexual individuals 372

Reproductive behavior 373
  Brood-pouch formation 373
  Incubation 374
  Pairing, fertilization, and burrow construction .. 375
  Size of brood 379

Discussion 384

Summary 385

Literature cited 387

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[1] Contribution from the Scripps Institution of Oceanography, new series, 740. These studies were aided by a contract between the Office of Naval Research, Department of the Navy, and the University of California, S.I.O., NR 163-084.

INTRODUCTION

A study of the biology of an organism necessarily involves the accumulation of data concerning many aspects of its anatomy and behavior. Knowledge about the way in which an animal reproduces, maintaining itself in its environment, is highly significant to an understanding of its biology. Here the external and internal anatomy of the marine pest *Limnoria* is described. Comparisons are made with other isopods in order that an idea may be had of the basic similarities and differences which *Limnoria* shows with the members of the crustacean order to which it belongs. Where possible, correlations are drawn between the structure of the reproductive system and the reproductive behavior of the animal.

This paper represents the results of part of a general study on the biology of *Limnoria* which was done under contract with the Office of Naval Research at the Scripps Institution of Oceanography in the Division of Marine Invertebrates in collaboration with Dr. Martin W. Johnson.

The first study of the internal anatomy of *Limnoria* was made by P. P. C. Hoek (1893, 97 pp., 7 pls.). Although written in Dutch and thus largely unavailable to American scientists, his work represents a most comprehensive study which has often been quoted and which forms the basis for a similar report by Kofoid and Miller (1927, pp. 306-332). Both investigations dealt with the entire organism, with only brief reference to the reproductive system. Various aspects of the reproductive behavior of *Limnoria* are also mentioned briefly by Coker (1923, pp. 95-100), Henderson (1924, p. 320), Johnson (1935, p. 428), Sømme (1940, p. 155) and Shiino (1950, p. 348), all of whom were mainly interested in the ecology of the animal.

MATERIALS AND METHODS

The species investigated was *Limnoria tripunctata* Menzies (Menzies, 1951, pp. 86-88) collected from San Diego harbor, California. Its reproductive system has been compared with those of *L. quadripunctata* Holthuis and *L. lignorum* (Rathke). No structural deviations of major importance were found, and it is therefore believed that the findings reported here are applicable to the majority of the species.

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Living specimens, whole and decapitated, were fixed prior to sectioning, in formalin (10 per cent), Carnoy's fluid acid alcohol, formalin-alcohol-acetic acid (F.A.A.), and 70 per cent alcohol. Cytological details were best preserved in decapitated specimens fixed in F.A.A. Sections were made of paraffine-embedded samples at 7 μ and 10 μ. Three staining techniques were employed: Heidenhain's iron hematoxylin (counterstain eosin), Mallory's triple stain, and Harris' hematoxylin. The first gave the most generally useful results for this study.

COMPARATIVE MORPHOLOGY OF THE REPRODUCTIVE ORGANS

In common with all known isopods the body of *Limnoria* can be divided into three major regions (Fig. 1): the cephalon or head bearing the eyes, antennae, and mouth parts; the peraeon or thorax bearing usually seven pairs of walking legs; and the pleon or abdomen bearing usually five pairs of swimming and respiratory appendages, the pleopods. The male and female gonads are contained within the peraeon. Their relationship to other major organs is shown in Figure 2. In *Limnoria* the sexes are separate but this is not true for several other isopods (p. 372). The body of an adult *Limnoria tripunctata* is roughly 2.50 mm. long and 0.60 mm. wide at the pleotelson.

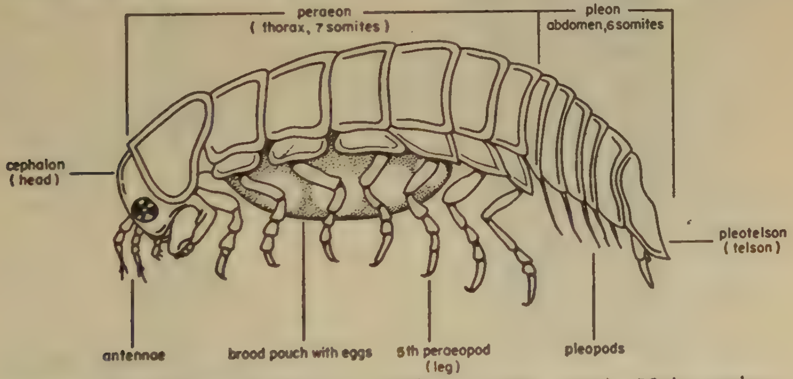


Fig. 1. Gravid female *Limnoria* (from G. O. Sars, 1897). Major regions of the body mentioned in text are noted. (The assistance of Mr. Robert Winsett, Scientific Illustrator, Publications Division, S.I.O., in the final preparation of Figures 1, 2, 5, 6 is particularly appreciated.)

Internal Anatomy

Female. The ovaries are paired organs located below and on either side of the tubular heart and above the intestine and digestive glands. Each ovary when mature extends from the second to the seventh (last) peraeonal somite. Both their size and extent are governed by the size and number of the developing ova. The immature ova (Fig. 3C) are about 0.045 mm. along the long axis and have a characteristic uniform cytoplasm when preserved, and a discrete nucleus. Yolk globules are not differentiated. In contrast, the mature ova (Fig. 4) are large oblong yolk-filled cells with a length of 0.30 mm. and a cross-sectional diameter of 0.12

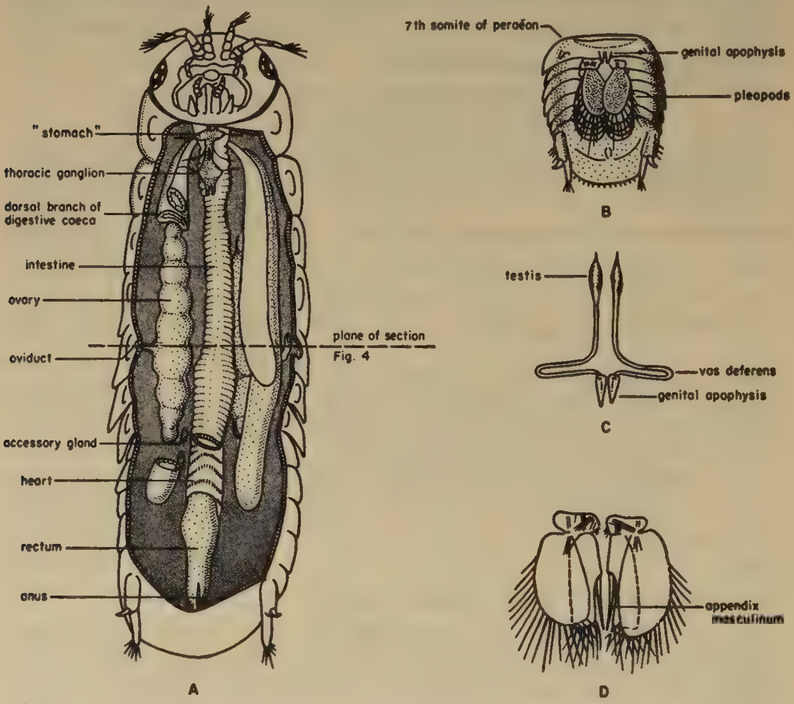

"stomach"
thoracic ganglion
dorsal branch of digestive caeca
intestine
ovary
oviduct
accessory gland
heart
rectum
anus
plane of section Fig. 4
A
7th somite of peraeon
genital apophysis
pleopods
B
testis
vas deferens
genital apophysis
C
appendix masculinum
D

Fig. 2. Internal and external reproductive organs of *Limnoria*. A. Female, ventral view, body wall cut away. B. Male, pleon and seventh somite of peraeon, ventral view. C. Testes. D. Second pleopods of male. Figures B and D after G. O. Sars, 1897; A and C original.

to 0.18 mm. The space occupied by the eggs at the middle of the body is equal to about 30-40 per cent of that of the expanded body cavity itself. The increased volume of the maturing eggs compresses the other internal organs to the extent that females in the stage prior to egg deposition frequently do not have food in the gut.

The oviduct, attached laterally to each ovary at about its middle, extends ventro-laterally to open at the base of the fifth pair of legs. Each oviduct is band-shaped with a length of 0.08 mm., a thickness of 0.01 mm., and a height (distance between ovary and orifice of oviduct) of 0.12 mm.

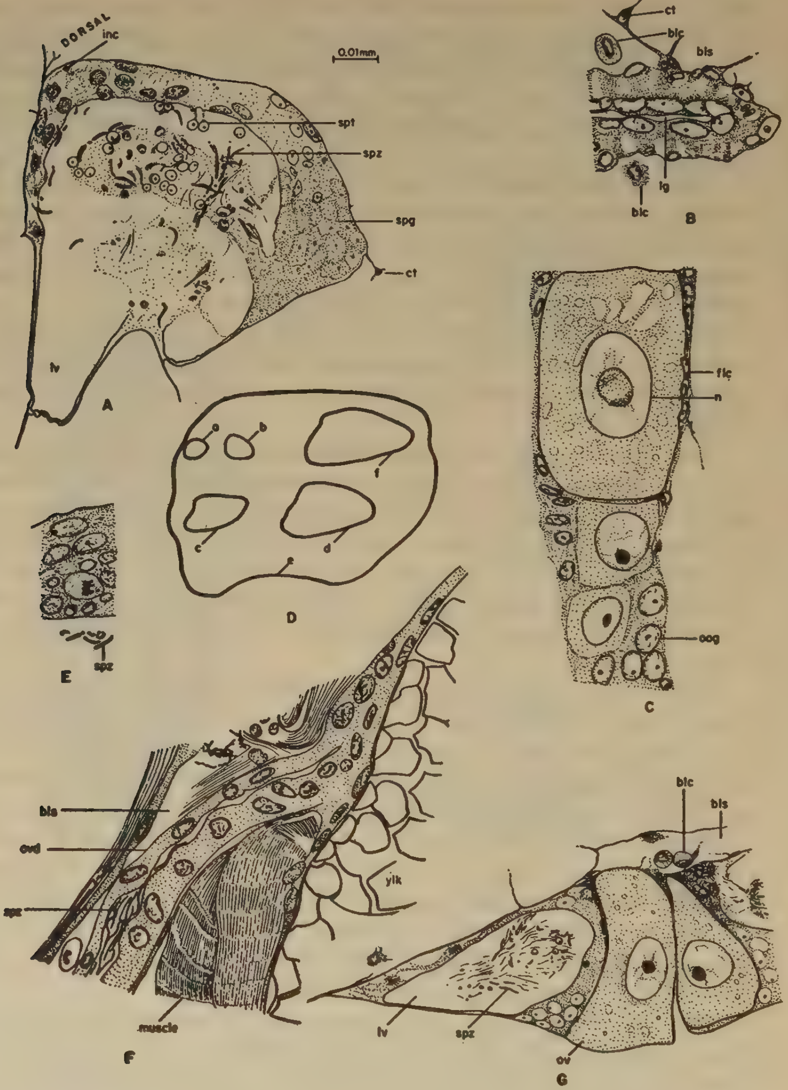
Much of the tissue surrounding each ovum consists of follicle cells (*flc*, Fig. 3C). The oogonia are distributed along the lateral margin of each maturing ovum and at the ends of the ovary (*oog*, Fig. 3C).

Posterior to each ovary are located two elongate glands which have a narrow lumen (called accessory glands by Kofoid and Miller). The function of these is not known. Dorsally they are in contact with the pericardium. Their cells (Fig. 3B) are unlike those of the ovary or any other organ in *Limnoria*. The location of the accessory glands near the heart and their presence only in the female suggest that they might have an endocrine function.

Male. The testes of the male are similarly paired (Figs. 2C, 3A). Each testis consists of a single lobe of approximately 0.08 mm. in diameter and 0.1 mm. in length, located between the fourth and fifth peraeonal somites, below and on either side of the heart and not in the last (7th) peraeonal somite as maintained by Kofoid and Miller (1927, *op cit.*).[1] A vas deferens proceeds from the testis to the seventh peraeonal somite. Here, as is usual for isopods, it turns medially and extends along the ventral body wall to one of the paired genital apophyses. The genital apophyses (=penis) consists of a pair of movable skin folds on either side of the midline of the seventh peraeonal somite.

The structure of the testis is unusual in having only a single lobe. Cytologically, spermatogenesis and spermiogenesis (Fig. 3A) are easily traced. Spermatogonia consist of rectangular shaped cells of uniform consistency and with an evident nucleo-

[1] Kofoid and Miller's error might be due to the mistranslation of Hoek's (*op. cit.*, p. 33) statement that the testes were located in the last body segments: "De testes nemen in de laatste borstsegmenten . . ."


DORSAL
inc
0.01mm
spt
spz
spg
ct
lv
A
ct
blc
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C
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f
c
d
e
D
spz
E
bls
ovd
spz
ylk
muscle
F
blc
bls
lv
spz
ov
G

lus. Primary spermatocytes have a greatly swollen nucleus and at the metaphase show tightly compacted tetrads and evident centrosomes. The nuclei of secondary spermatocytes are about one-half the size of those of primaries and have peripheral chromatin granules and an evident nucleolus. Spermatids show a variety of structure during their maturation to sperms. The nuclei of early spermatids have a granular nucleoplasm and apparently two nucleoli. Those in a later stage are much smaller with a clear nucleoplasm and two marked nucleoli. Mature sperm have a cap (head?), an elongate midpiece, and a tail piece which is at least twice the length of the midpiece. The precise length of the sperm tail was not determined. Various parts of the testis appeared to be in different phases of development. Morphologically mature sperm, however, were found in the lumen throughout the length of the testis. A hyaline membrane covered the testis and formed the wall of the vasa deferentia. It was associated with minute nuclei of the connective tissue outside the testis and appeared to have been secreted by those cells. Some small nuclei found inside the testis are considered to belong to interstitial cells.

It is common among isopods for sperm to mature together in compact batches (spermatophores). This bunching of sperm was not observed, however, to occur in *Limnoria*, and no spermatophore seems to be produced. Except for this deviation, the

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Fig. 3. Sections of reproductive organs of *Limnoria* A-C, E-F. A. Cross section through testis. B. Longitudinal section through part of an ovarian accessory organ. C. Longitudinal section through immature ovary. E. Part of a cross section through testis showing large primary spermatocytes and smaller secondary spermatocytes. F. Section through oviduct of fertilized female; note sperm in oviduct. *Abbreviations: blc*, bloodcell; *bls*, blood sinus; *ct*, connective tissue; *inc*, interstitial cell; *flc*, follicle cell; *lg*, lumen of accessory gland; *lv*, lumen of vas deferens; *n*, nucleus; *oog*, oogonium; *ov*, ovum; *ovd*, oviduct; *spg*, spermatogonia; *spt*, spermatid; *spz*, spermatozoa; *ylk*, yolk.

D. Outlines of second pair oostegites of *L. quadripunctata*, all drawn to same scale. Widths of pleotelsons of specimens in millimeters are: *a*, 0.59, *b*, 0.65, *c*, 0.70, *d*, 0.77, *e*, 0.77, *f*, 0.88.

Sections all drawn to about the same scale as indicated in figure A; all drawings were done with the aid of a camera lucida.

testis cytologically appeared much like those described for other isopods.

A sperm storage organ or seminal receptacle has been discovered in many of the female isopods whose internal anatomy has been studied. This includes *Trichoniscus, Asellus,* and *Jaera* (Fig. 5). In *Jaera* and *Asellus* the seminal receptacle consists only of a swollen part of the oviduct, but in *Trichoniscus* a separate pouch is present. The genus *Jaera* shows an apparently unusual modification in also having a dorsally-opening vagina. Female *Limnoria* appear to lack any sperm storage organs and in this regard are apparently similar to *Sphaeroma.*

External Anatomy

The secondary sex characteristics of the female consist of leaf-like plates (oostegites) originating at the medial base of the coxal plate of legs two, three, four, and five; and of the paired openings of the oviducts medial to the base of each fifth leg. With the absence of a vagina in the genus, each of these openings might be considered a vulva. The vulvae were not found in immature females. Similarly the oviducts seemed to remain closed (without a lumen) until a short time prior to copulation.

The male secondary sex characteristics consist of the genital apophyses (Figs. 2C, 6) which were already mentioned and a stylus-like appendage (appendix masculinum) attached on the medial side of the endopod of each second pleopod (Fig. 2D).

The secondary sex characteristics of isopods show some remarkable variation. For example, oostegites do not appear in the suborder Gnathiidea (Monod, 1926, pp. 202-210), Fig. 5E, although the area of the ventral part of the body surrounding the genital atrium might be considered homologous. Oostegites, as indicated for *Limnoria,* are present in most members of the suborders, e.g. Anthuroidea, Flabellifera, Bopyroidea, Valvifera, Asellota and Oniscoidea. The movable plates which form the genital apophyses of *Limnoria* develop from simple swellings of the integument. Such swellings constitute the adult condition in *Cymothoa* (Fig. 6G). A fusion of these lobes into a single piece (ductus ejaculatorius) seems to have occurred in at least two suborders independently. Thus *Idothea* (Valvifera) has two plates, whereas *Synidotea* has one (Valvifera). *Ligidium* has two, while *Philoscia*

(Fig. 6C) has one (Oniscoidea). An appendix masculinum is present on the endopod of the second pleopods of males belonging to the suborder Flabellifera. Here its function is not known but it has been presumed to act as an intromittent organ in passing the sperm from the genital apophyses to the vulva (or equivalent opening) of the female. In the suborder Asellota (the genus *Asellus* perhaps being exceptional), the first two male pleopods combine as a functional penis. This is the case also in the suborder Oniscoidea (Vandel, 1925); however, the pleopods are of a structure quite different from those of the Asellota (Fig. 6D).

Within the suborder Flabellifera, each appendix masculinum consists only of a flattened part of the endopod of the second pleopod which originates by splitting off the endopod. In most genera it is within the realm of possibility that the appendix is long enough to reach the oviducal opening of the female; however, on the appendix masculinum of *Limnoria* the lack of any grooves, specialized bristles, or rugosities, in which sperm might be transferred or held prior to or during copulation, suggests that the appendix masculinum might not have such a function. On the other hand, the genital apophyses are generally so short and located so near the midline of the male that it is difficult to imagine that these might reach the vulvae of the female which in contrast are located at the base of the legs of the female, far from the midline. Copulation among the Flabellifera has not been observed in detail and, therefore, no solution to the above puzzle is offered.

SEX DETERMINATION

Sex Ratio

The sexes of *Limnoria* are found in about a 50/50 ratio when taken from piling populations (Station A,[1] mean ratio of males to mature females, 0.95, and Station B,[2] mean ratio of males to mature females, 1.06; see Table 1). It is probable that males and females are produced in that ratio; however, this needs further confirmation. The presence of sex chromosomes might be suggested for *Limnoria* and other marine isopods in view of the finding by Staiger and Bocquet (1954) of female heterogamety in the marine isopod *Jaera marina*.

[1] Located at the U.S. Navy Target Repair Base, Point Loma.

[2] Located near the San Diego landing of the Coronado Ferry.

TABLE 1

Ratio of males to females (those with oostegites) on piling. Specimens were taken from heavily infested wood, each sample averaging about 1 square inch in area.

Month	Station A	Station B
September 1952	0.95	0.83
October 1952	1.05	1.19
November 1952	1.26	0.93
December 1952	1.26	—
January 1953	1.12	1.31
February 1953	0.65	1.00
March 1953	1.20	1.00
April 1953	0.44	1.19
May 1953	0.95	—
June 1953	1.00	—
July 1953	1.92	—
August 1953	0.65	—
Mean	0.95	1.06
Mean Sta. A and B	0.99	

Ambisexual Individuals

Ambisexual animals, those having the primary and secondary characteristics of both sexes, were encountered rarely. Out of the 1423 sexually mature animals examined from thirteen migrant populations, they were found only twice; once in a sample having 39 specimens, and once in a sample having 137 specimens. Three were found out of a total of 657 specimens from piling; one sample of 91 animals had two while another of 30 animals had one. These individuals had the genital apophyses of the male as well as the immature or postgravid oostegites of the female.

Sections of one ambisexual individual (Fig. 3G) showed the presence of ovaries with immature ova as well as testes with mature sperm. No oviducts were found. Protandry is a characteristic feature of one family of the Flabellifera, the Cymothoidae, in which the young are functional males (with rudiments of ovarian tissue) and progressively become functional females. In the Sphaeromidae, rudimentary testes are attached to the ovaries of the female.

REPRODUCTIVE BEHAVIOR

Brood-Pouch Formation

The development of the oostegites prior to copulation and brood deposition is a gradual process with their size increasing as the animal grows (Fig. 3D). Copulation, fertilization, the production of the large oostegites of the fully formed brood pouch, and egg deposition into the pouch of *Limnoria* all appear to take place within a brief period of time (probably no more than two or three days). The release of the young from the brood pouch is followed by a molt of the female (several laboratory observations) and a reduction in size of the oostegites to their pregravid size (Fig. 3D). This was suspected earlier to be the case when females with small oostegites were found to have apparently recently released young in their burrows. It follows then that females with pregravid oostegites can be either virgin

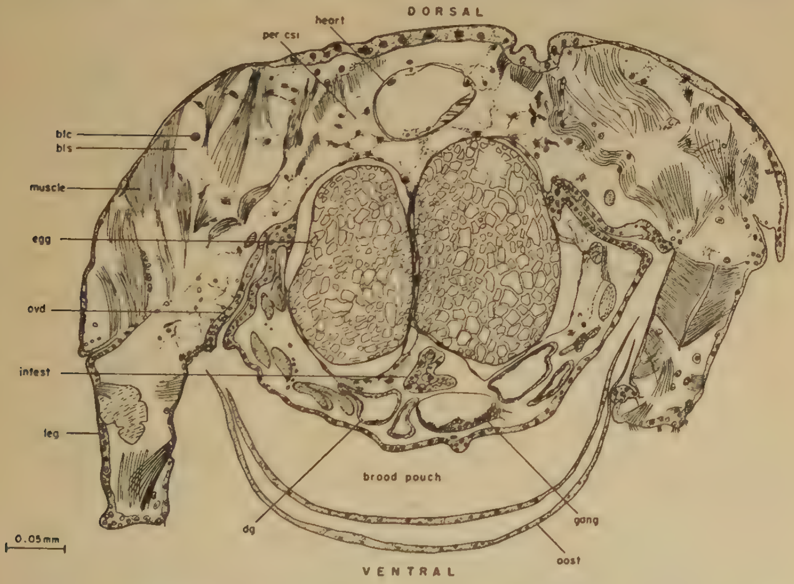

Fig. 4. Cross section through pre-gravid female *Limnoria* at oviduct. The animal had molted and the chitin was not heavily sclerotized at this stage. Note huge size of eggs and absence of food in intestine. Abbreviations, same as for Figure 3 with the following added: *dg,* digestive gland; *gang,* ganglion; *intest,* intestine; *oost,* oostegite; *per csi,* pericardial sinus.

females or females which have already produced one or more broods.

Incubation

Limnoria incubates its young within its external brood pouch (Fig. 5B). This mode of incubation is common to the majority of isopods, including the suborders Asellota, Oniscoidea, Valvifera, Anthuridea, Bopyroidea, Phreatoicidea, and most of the

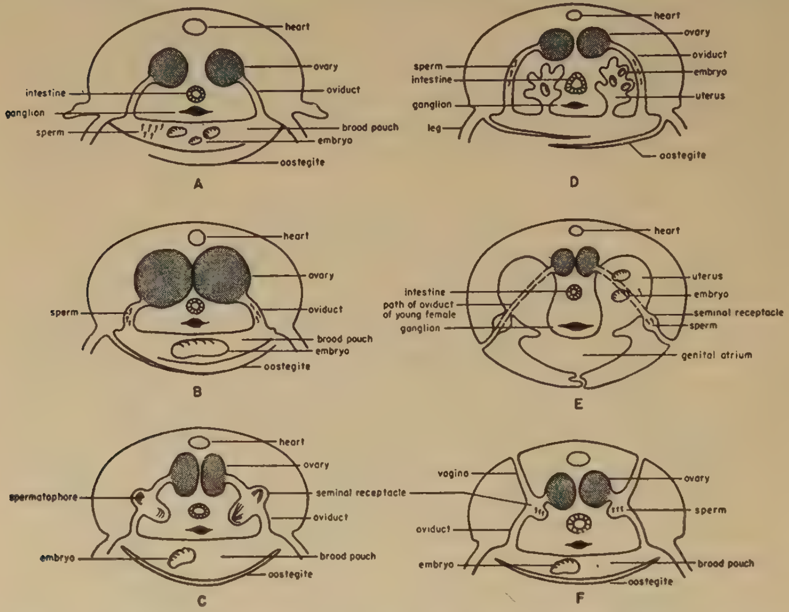
heart
ovary
intestine
oviduct
ganglion
sperm
brood pouch
embryo
oostegite
A
heart
ovary
oviduct
sperm
intestine
embryo
uterus
ganglion
leg
oostegite
D
heart
ovary
sperm
oviduct
brood pouch
embryo
oostegite
B
heart
uterus
intestine
embryo
path of oviduct
of young female
seminal receptacle
ganglion
sperm
genital atrium
E
heart
ovary
spermatophore
seminal receptacle
oviduct
embryo
brood pouch
oostegite
C
vagina
ovary
sperm
oviduct
embryo
brood pouch
oostegite
F

Fig. 5. Schematic diagrams of the female reproductive systems of the Isopoda. A. *Epipenaeon,* note external fertilization and absence of sperm storage organs. B. *Limnoria,* note absence of sperm storage organs. C. Oniscoid isopods, note presence of seminal receptacle and/or spermatophores. D. *Sphaeroma,* note presence of uterus and functionless "brood pouch." E. Adult *Paragnathia,* note absence of brood pouch and modifications undergone by female in development. F. *Jaera,* note presence of dorsal vagina. Figure A based on data from Hiraiwa (1936); B, original; C, from Vandel (1925); D, from Leichmann (1891-93); E, from Monod (1926), young based on figures given by Monod, adult from description by Monod; F, from Forsman (1944).

Flabellifera. The Gnathiidea and the Sphaeromidae (suborder Flabellifera) incubate their young "internally." In the Sphaeromidae the eggs are deposited into the brood pouch but then are taken into uteri which consist of paired invaginations of the ventral body wall. In the Gnathiidea no brood pouch is formed; instead the eggs are deposited into a genital atrium and then taken into the uteri which are reminiscent of those of the Sphaeromidae.

Pairing, Fertilization, and Burrow Construction

The occupation of a burrow usually by only a sexually mature male and female (plus any young produced by the pair) has been

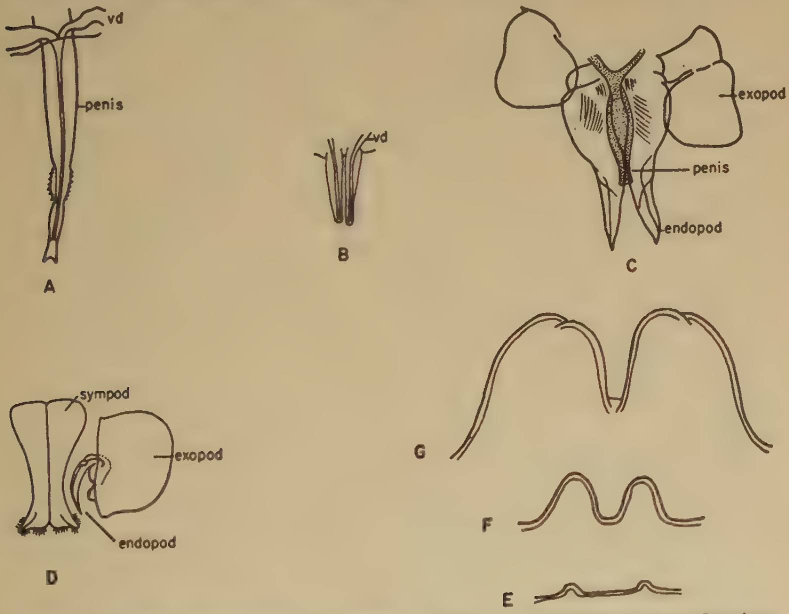

Fig. 6. Male reproductive organs. A. Penis of *Trichnoiscus dentiger* (after Vandel, 1925), B. Genital apophyses of *Ligidium hypnorum* (after Vandel, 1925), C. First pleopods and penis of *Philoscia muscorum* (after Vandel, 1925), D. First two pleopods of *Ianiropsis* sp. (after Menzies, 1952), E-G. Genital apophyses, E. Adult *Cirolana*, F. Young *Limnoria*, G. Adult *Cymothoa*, all original. Scales of magnification variable. Abbreviations same as for other figures, *vd*, vas deferens.

TABLE 2

A comparison of the length of burrows occupied by single or by paired animals on test blocks of one- and two-month exposure at the U.S. Naval Target Repair Base, San Diego harbor, California (1953).

Burrow Length in mm.	No. Burrows with Single Animals		No. Burrows with Paired Animals	
	One-Month	Two-Month	One-Month	Two-Month
1.5	3	3	0	0
3.5	42	13	2	0
5.5	11	10	16	2
7.5	1*	6	12	8
9.5		1*	24	16
11.5			2*	14
13.5				10
15.5				9
17.5				2
19.5				1
21.5				1
23.5				1*
Total	57	33	56	64
Mean Burrow Length	3.8±0.97	4.8±1.95	7.6±1.9	11.8±3.4

* Length of longest burrow.

frequently observed (Henderson [1924], Johnson [1935], Shiino [1950], etc.). Examination of burrows in test blocks revealed that a burrow generally had two animals only when long enough to fully enclose two specimens (around 5.5 mm. and longer). The proportion of paired animals was found to increase markedly as the length of burrows and the length of exposure to migrant populations increased. Test blocks of one-month exposure had about as many burrows occupied by one as occupied by two animals, while those of two-month exposure had twice as many paired organisms as single ones (Table 2). Organisms kept in the laboratory have been observed to pair with each other for periods exceeding ten months (one case) and four months (four cases); presumably a similar relationship between paired sexes can be expected to occur in nature. Accordingly, it appears that the pairing of sexually mature animals within a burrow is an essential and consistent feature of their biology.

Copulation apparently occurs in the burrow. The sperm produced by the male are relatively few in number and these, as has been seen, are not combined into a spermatophore. Sperm have been found in the oviduct of the female and probably fertilize the eggs as they pass down the oviducts. The absence in the female of any seminal receptacle suggests that a copulation must precede the deposition of each brood. This is more strongly indicated by the observation that sperm were not found in the oviducts of females bearing embryos or in virgin or post-ovigerous females but only in those with ripe ovaries which were molting, prior to egg deposition (Fig. 3F). In the terrestrial isopods which have been extensively studied in this regard and which bear a seminal receptacle, a single copulation has been found sufficient for the production of two broods (*Armadillidium*, Howard, 1940, p. 84). Heeley (1941, pp. 136-137) reports viable sperm to have been stored by isolated females of *Porcellio dilatatus, P. scaber* and *Oniscus asellus* for at least two successive year's brood. The sexes of *Porcellio* and *Armadillidium* show no tendency to pair and in the case of the latter, natural populations often have twice as many of one sex as the other (Howard, *op. cit.*). Oniscoid isopods (*Porcellio, Trichoniscus, Armadillidium,* etc.) usually have a seminal receptacle and the males produce many sperm which are united into a spermatophore (Schöbl, 1880; Vandel, 1925). In contrast, it is interesting to note that the diverse genera in which a long-term sexual pairing is a pronounced characteristic of the animals, no seminal receptacle is known to exist. These include the bopyrid, *Epipenaeon,* in which fertilization is apparently external (Hiraiwa, 1936, p. 108), the commensal and parasitic cymothoid, *Anilocra physoides* (Montalenti, 1941, pl. XIX), and *Sphaeroma* (Leichmann, 1891). It appears that pairing, a long-term association of members of the opposite sex, is correlated generally with an absence of sperm storage organs in the species which have been studied. In *Limnoria,* in view of its pairing habit, the production of sperm storage organs would teleologically seem superfluous.

There exists the remote possibility that parthenogenesis (which is known for several species of terrestrial isopods) might occur in *Limnoria.* Five females kept for one year without a male failed to produce any brood, whereas seven paired animals produced one to two broods during that time. Hence parthenogenesis by *Limnoria* is considered unlikely.

TABLE 3

Size of broods (egg number) produced by various isopods

Classification	Species	Reference	Brood Size
ONISCOIDEA			
Ligiidae	*Ligia oceanica*	Vandel, 1925	25
	Ligidium hypnorum	“ “	3-17
Trichonisidae	*Trichoniscus provisorius*	“ “	3-19 (7-11 av.)
	Trichoniscus flavis	“ “	6-18 (12 av.)
Oniscidae	*Tracheoniscus rathkei*	“ “	63
	Porcellio monticola	“ “	73
	Porcellio scaber	“ “	88
	Oniscus asellus	“ “	74
Armadillidiidae	*Armadillidium vulgare*	“ “	up to 200
FLABELLIFERA			
Cymothoidae	*Anilocra physodes*	Legrand, 1952	100-350
	Livoneca convexa	Original	67-130
Limnoriidae	*Limnoria* spp. (4)	This paper, p. 380	1-32 (6-21 av.)
Sphaeromidae	*Sphaeroma rugicauda*	Leichmann, 1891-93	63
GNATHIIDEA			
	Paragnathia formica	Monod, 1926	100+ (in ovary)
ASELLOTA			
Janiridae	*Jaera albifrons*	Forsman, 1944	5-60
	Desmosoma spp. (3)	Hult, 1941	8, 12, 16 (av.)
	Ilyarachna sp.	“ “	64
Munnopsidae	*Munnopsis typica*	“ “	32 (greatest number)
ANTHURIDEA	No data available		
BOPYROIDEA			
Bopyridae	*Epipenaeon*	Hiraiwa, 1936	2000+ (“several thousand”)
VALVIFERA			
Idotheidae	*Idothea (P.) resecata*	Original	46 (29-65)

Size of Brood

The size of the broods produced by *Limnoria* is comparatively small and variable both with regards to species and differing populations of the same species.

Isopods with pelagic young (bopyrid parasites) characteristically produce thousands of eggs per brood (Table 3). Other marine isopods belong to a category of marine organisms which produce fewer than a thousand young per brood (Thorson, 1950, p. 4). No free-living form is known to brood an excess of three hundred eggs.

The members of the genus *Limnoria* produce an average maximum of only 30 eggs per brood. Since few marine animals, even isopods, produce a smaller number of eggs, *Limnoria* may be classified with those marine animals which produce only a few eggs at one time. Except for the correlation between pelagic development of young and a high egg number, which is the rule among marine invertebrates, egg number among the isopods shows no pronounced phylogenetic correlation or pronounced correlation with size. Thus, within the suborder Oniscoidea, egg number per brood varies between 3 and 200, and in the suborder Flabellifera between 32 and 350. The size of the species is not a significant factor governing egg number because *Ligidium hypnorum*, a species much larger than *Limnoria*, does occasionally produce even fewer eggs than *Limnoria*. Similarly cymothoids which are generally much larger than many bopyrids produce several times fewer eggs. The number of eggs produced by an isopod seems more intimately related to the ecology and behavior of the species, and those factors influencing survival rate, than to other factors. One might suspect, in the burrow-producing *Limnoria*, that the survival rate of the young is very high in view of the animal's small brood size.

To judge from the available data on brood size (Table 4), it appears that the different species of *Limnoria* have differing brood sizes. Thus *L. lignorum* has been observed with a maximum of 35 eggs (mean 22), *L. quadripunctata* with 17 eggs at a maximum (9.5 mean), *L. tripunctata* with a maximum of 22 eggs (*ca.* 4-10 on an average), and finally *L. andrewsi* with a maximum of only 6 eggs. Here it is interesting to note that *L. lignorum*, a boreal species, has the greatest number; whereas, *L. andrewsi*, a tropical species, has the least.

The evidence thus far assembled does not conclusively suggest, as has been the observed case for many organisms, that younger specimens (smaller) produce fewer eggs than larger specimens. In the species *Limnoria lignorum* (Rathke), Sømme (1940) reported that broods produced during the summer were on an average larger by 10-12 eggs than autumn broods. Coker (1923)

TABLE 4

Number of eggs per brood in several species of *Limnoria*

Species	Kind of Distribution	Reference	Locality	Egg Number	
				Mean	Range
L. lignorum (Rathke)	Arctic-Boreal	Henderson (1924)	St. Andrews, Bay of Fundy	21.7	14-32
		Johnson (1935)	Friday Harbor, Washington	—	10-23
		Sømme (1940)			
		a. summer broods	Flødvigen, Nor.	20-30	20-35
		b. autumn broods			10-20
L. quadripunctata Holthuis	Temperate	Kofoid and Miller (1927)	San Francisco Bay, Calif.	9.5	1-17
L. tripunctata Menzies	Temperate	Coker (1923) piling populations	Beaufort, N.C.		
		a. early spring broods		4.2-6.6	1-12
	and	b. summer broods and fall		1.5-4.0	1-9
		c. winter broods		none	none
	Tropical	Shiino (1950)	Misaki, Japan	—	1-8
		ORIGINAL			
		a. piling populations	San Diego, Calif.	4.6±2.74	1-14
		b. Test-block population A	San Diego, Calif.	10.6±3.94	1-18
		c. Test-block population B	San Diego, Calif.	9.6±4.24	1-22
L. andrewsi Calman	Tropical	Shiino (1950)	Kominato, Japan	*ca.* 4-5	2-6

conversely found spring broods larger than summer and fall broods by several eggs (Table 4). He found no gravid females during the winter months. During the spring (April to May) the mean water temperature was near 17°C; during the summer and fall (June to September) it was near 26°C and never below 22°C. In contrast the 5-day averages of the winter water temperatures (December 13 to early March) varied between 11.3°C and 5.2°C. His data strongly suggest a close correlation between temperature and the production of eggs and a less strong correlation between temperature and brood size. Coker probably was working with *tripunctata* (not *L. lignorum*) which is the only species known to occur in North Carolina. As far as is now known *L. lignorum* does not occur south of Massachusetts on the Atlantic Coast.[1]

Sømme (*op. cit.*) found gravid females of *L. lignorum* throughout the year with maximal numbers occurring at temperatures averaging only 9°C and lesser numbers occurring when the temperatures averaged 3.9°C. During periods having similar water temperatures Coker (*op. cit.*) found no gravid females of *L. tripunctata.* Sømme's evidence (*op. cit.*) indicated that little or no egg deposition occurred during the winter months but that the eggs deposited earlier were carried throughout the winter by the female.

These data indicate that an optimal range of temperature for the production of maximal-sized broods might occur in both species.

The presence of gravid females of *L. tripunctata* from piling in San Diego harbor and their absence from test blocks of one-month exposure during the winter months, when the temperature of the water was below 17°C, suggests a similar phenomenon; however, their presence on test blocks of two-months' exposure strongly indicates that egg deposition does not cease entirely as Coker found at Beaufort, but is only retarded under these less extreme conditions (Table 5).

In the case of *L. tripunctata* from San Diego harbor where temperatures near to Beaufort's spring temperatures (17°C) prevailed, it seems that factors besides temperature govern brood size. It has been found that migrant females (those from test

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[1] Unpublished data.

TABLE 5

Seasonal occurrence of gravid females in piling and test-block samples in San Diego harbor.

MONTH	MEAN WATER TEMPERATURE (approximate)		PILING		TEST-BLOCK				TEMPERATURE AT COLLECTION
					One-Month Exposure		Two-Month Exposure		
		Temp. at Collection	Per cent Gravid Females	Total Mature Females Examined	Per cent Gravid Females	Total Mature Females Examined	Per cent Gravid Females	Total Mature Females	
September 1952	17-18°C	17.8	52	63	10	78			**17.4
October 1952		18.0	27	22	36	25	33	**33	**18.8
November 1952		16.9	22	37	8	12			**16.9
December 1952		15.1	5	20	*0	21	68	**22	**14.8
January 1953	15°C	14.9	12	25	*0	6			**14.0
February 1953		14.9	25	20	*0	14	72	**22	**15.4
March 1953		15.3	21	19	*8	13			
April 1953		14.1	32	38	*3	34	54	13	
May 1953	17-18°C	16.6	11	19	29	42			
June 1953		18.2	30	47	10	40	67	12	
July 1953		19.7	15	13	7	27			
August 1953		18.6	50	46	41	27	73	15	

* Sum of animals from three blocks, others from one block only.
** Year 1953 to 1954, not 1952 to 1953 as are all others.

blocks) produce an average of 5 more eggs per pouch than nonmigrants (those from piling populations). The variable factor which correlates best here is differences in population density. The mean number of animals per square inch on test blocks of one-month exposure (Station A) from the top and bottom surfaces of the blocks for one year was 3.9.[1] The maximum density encountered (August 13, 1953) on those surfaces was 60 per sq. in. In contrast the density of piling populations (also sampled monthly at Station A) varied between 142 (lowest figure) and 620 (highest figure) animals per square inch (Table 6). A similar relationship between population density and fecundity has been indicated by Park (1939) for the flower beetle *Tribolium confusum.* It is equally difficult in the case of *Limnoria* to prove the *modus operandi* of a population density factor in lowering the fecundity of a population.

The fact that different species have differing brood sizes is of considerable interest indicating that perhaps the ecological factors associated with the reproductive capabilities of the various species are also different. Differences may be found in the frequency with which the broods are produced but this is an item about which no data are available at present.

TABLE 6

Egg number per brood of females from a piling population (presumably nonmigrant) and a test-block population (migrant) compared. Data collected at monthly intervals (1952-53) for twelve-thirteen months in San Diego harbor at two widely separated stations.

Location	Number of Gravid Females Examined	Mean Number of Eggs	σ ±	Range
Piling, Sta. A.	307	4.66	2.70	1-14
Test-block, Sta. A.	105	10.06	3.94	1-18
Test-block, Sta. B.	113	9.63	4.27	1-22

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[1] An empirically determined ratio of 1.5 animals times the number of burrows has been used here to estimate the total population of each test-block.

DISCUSSION

From this study it is apparent that the reproductive system of *Limnoria,* except for the fact that fertilization is internal, is a simple one with none of the specializations such as a vagina, spermatophore, seminal receptacle, or ''internal'' uterus which are known for many other isopods. Correlated with this simplicity of structure is the tendency of an adult of each sex to occupy a single burrow for long periods of time. This latter phenomenon suggests that *Limnoria* shows an elementary social life, with the paired animals working together in the construction and maintenance of a burrow and the production of the young.

The observation that the size of the brood of the various species is different, with the more tropical species having a fewer number of eggs than the species living in colder water, suggests that the rate at which broods are produced might be different with the different species. The fact that the rate of production of broods is dependent upon the environment inhabited by a species (as indicated by the data given here and earlier by Coker [1923] and Sømme [1940]) strongly suggests that the rate of brood production is not constant. These observations lead to a method for the evaluation of one hypothesis as to the cause of migration by *Limnoria,* namely overcrowding of the burrows. Once production rates for species in various localities and during various seasons are determined, these may be compared with the migratory picture, and a relationship based on more direct evidence can be established. The data indicate another important item relative to brood production, namely that both high and low temperatures encountered by a species can be associated with a lowering of the brood size. A rising environmental temperature then cannot be presumed always to be accompanied by a corresponding rise in the size of broods or in the rate of brood production.

Perhaps the most significant observation, one which should play a profound role in an estimation of the productivity of natural populations, is that the brood size of specimens from dense piling populations was found to be significantly lower than that of specimens from less dense migrant populations. Investigation of the factors associated with this observation should lead to a better understanding of the population dynamics of this species as such investigations have done with other organisms for which this phenomenon has been reported.

SUMMARY

1. The internal and external anatomy and general histology of the reproductive organs of *Limnoria tripunctata* Menzies are described and compared with those of other isopods.
2. The male was found to have one-lobed testes in contrast to most isopods and was found not to produce spermatophores.
3. The female was found to have no sperm storage organs. Sperm were observed in the oviducts and it is believed that fertilization of the eggs occurs as they are passed down the oviducts into the brood pouch.
4. The absence of spermatophore production by the male, the absence of sperm storage organs in the female, and the finding of sperm in the female oviduct only prior to egg deposition suggest that a copulation must precede each brood.
5. The method of copulation was not observed. The simple unmodified structure of the appendix masculinum suggests that it is possibly not involved in sperm transfer.
6. A sex ratio of one male to one female is suggested from piling population analysis.
7. Ambisexual individuals were rarely encountered. These individuals had the genital apophyses of the male as well as the oostegites of the female externally and both testes and ovaries internally.
8. It was found that oostegites gradually increase in size until, within one molt, they suddenly increase greatly to form the brood plates of the brood pouch of the gravid female. A release of the young was observed to be accompanied by a molt of the female and a return of the oostegite to a pregravid size. Accordingly, it is indicated that females with pregravid oostegites can be either virgin females or females which have produced one or more broods.
9. The long-term pairing of a sexually mature male and a female in a burrow apparently is an essential and consistent feature of the biology of *Limnoria*. Specimens have been observed to remain paired as long as ten months.

10. The pairing behavior of *Limnoria* and that of several other isopods appears generally to be associated with an absence of any sperm storage mechanism.

11. The reproductive system of both sexes of *Limnoria* is simple in its organization as compared with that of other isopods.

12. Parthenogenesis does not appear to occur in *Limnoria.*

13. *Limnoria* belongs to a category of isopods which produce only a few eggs (average maximum of 30) per brood. A high survival rate of the young and/or a rapid rate of production is indicated.

14. Brood size was found to vary both with regards to the species and differing populations of one species.

15. The boreal species *L. lignorum* (Rathke) produces as many as 35 eggs per brood, whereas the tropical *L. andrewsi* Calman produces only 6 at a maximum. The temperate and temperate-tropical species *L. quadripunctata* Holthuis and *L. tripunctata* Menzies were found to produce broods between those extremes in size.

16. Under conditions of moderately low temperature (near 10°C) at Beaufort, N. C., *L. tripunctata* produced no broods. The brood production of the same species at San Diego during the winter months (temperature near 15°C) was retarded but did not cease entirely.

17. The data suggest that both high and low temperatures are associated with a lowering of brood size in *L. tripunctata* at Beaufort, N. C.

18. At San Diego harbor where seasonal temperature variations are moderate as compared with Beaufort, N. C., variation in brood size was found to correlate with population density, with animals from piling populations (high density) having fewer eggs per brood than animals from test-block populations (low population density).

19. A method of testing the hypothesis that overcrowding is the cause of migration in this species is proposed.

20. The following factors are indicated as important in estimations of the production rate of *Limnoria*: a) species involved, b) temperature and its effect on brood size and rate of brood production within a single species, c) population density and its associated factors as they affect brood size.

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741

THE VOLCANO LETTER

No. 525 U. S. Geological Survey July-September, 1954

PUBLISHED BY THE UNIVERSITY OF HAWAII

VOLCANIC ERUPTIONS OF 1953 AND 1948 ON ISABELA ISLAND, GALAPAGOS ISLANDS, ECUADOR[1]

By ADRIAN F. RICHARDS[2]

1953 FLANK ERUPTION OF SIERRA NEGRA (Volcan Grande)

On August 27, 1953, the northern flank of Sierra Negra (Volcan Grande), situated on southern Isabela (Albemarle) Island, the largest of the Galapagos Islands, was reported in a state of eruption. The reports were contained in radio messages sent by the captains of several tuna clippers to the Scripps Institution of Oceanography, University of California, and the U. S. Hydrographic Office (Notice to shipmasters, volcanic activity, Pacific Ocean: U. S. Hydrog. Office, Hydrographic Bul. No. 36, Sept. 5, 1953). Joe Marques, Master, and Robert Robbins, Navigator and Radio Operator, of the "Normandie," and Captain George Zeluff of the "Paramount" have furnished the writer with their observations of the beginning of this eruption.

During the afternoon of August 27 a presumedly new lateral fissure, believed to trend northeast-southwest and estimated to be two miles long, opened about three-fourths of the way up the northern side of Sierra Negra, at an approximate altitude of 3,700 feet. The beginning of the eruption was witnessed from the "Paramount," located in Bolívar Canal nearly 30 nautical miles north of the fissure site. A very large, light-colored eruption column was observed to ascend to a height of more than 30,000 feet, and voluminous flows of lava started to issue from the ends of the fissure and flow north towards Elizabeth Bay.

During the night of August 28 a bright red reflection in the sky was observed from the "Normandie," which was then off the west end of San Cristobal (Chatham) Island, approximately 90 miles east of the volcano. On the 29th the eruption was viewed from the "Normandie" in Elizabeth Bay, about 20 miles from the fissure. Unfortunately much "smoke"—slightly darker than the fog—and haze obscured the site of the eruption. However, at night visibility improved, and cherry-red lava could be seen flowing down the northern side of Sierra Negra. Lava from the north end of the fissure appeared to flow due north, to the shore of Elizabeth Bay, about 5 miles from the fissure. It is not known whether or not the lava flowed into the bay. From the southern end of the fissure the lava stream apparently divided and flowed toward both sides of Point Moreno, which is located approximately 10 miles northwest of the fissure. "Red eruptions," probably lava fountains or showers of incandescent cinder, ascended an estimated 400 feet (as seen from 20 miles away) above the fissure at intervals of seven to eight minutes. Most of the visible activity appeared at the northern extremity of the fissure.

On August 31 a bright reddish glow, reflected from low clouds, was seen from James Bay on the western side of San Salvador or Santiago (James) Island, nearly 40 miles north-northeast of the volcano. On September 10 the "Normandie" was near Webb Cove, about 15 miles west of the fissure. Volcanic activity, if present, was not observed, due to heavy fog, mist, and clouds which obscured the island from view.

Ray Maderis, Navigator of the "Equator," has informed the writer that on October 7 volcanic activity on southern Isabela Island was observed from Baltra Island, about 60 miles to the northeast.

At the end of January, 1954, the "Paramount" again visited Isabela Island. Visibility from Elizabeth Bay was

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[1] Contribution from Scripps Institution of Oceanography, New Series, No. 741.

[2] Scripps Institution of Oceanography, La Jolla, California. The writer wishes to express his appreciation to all of the men of the tuna fishing fleet who have contributed the information which has made this report possible. The assistance of Professors F. P. Shepard and Chas. H. Behre, Jr., who have critically read the manuscript, is also appreciated. Professor Behre has also aided the writer with the nomenclature of the Isabela Island volcanoes.

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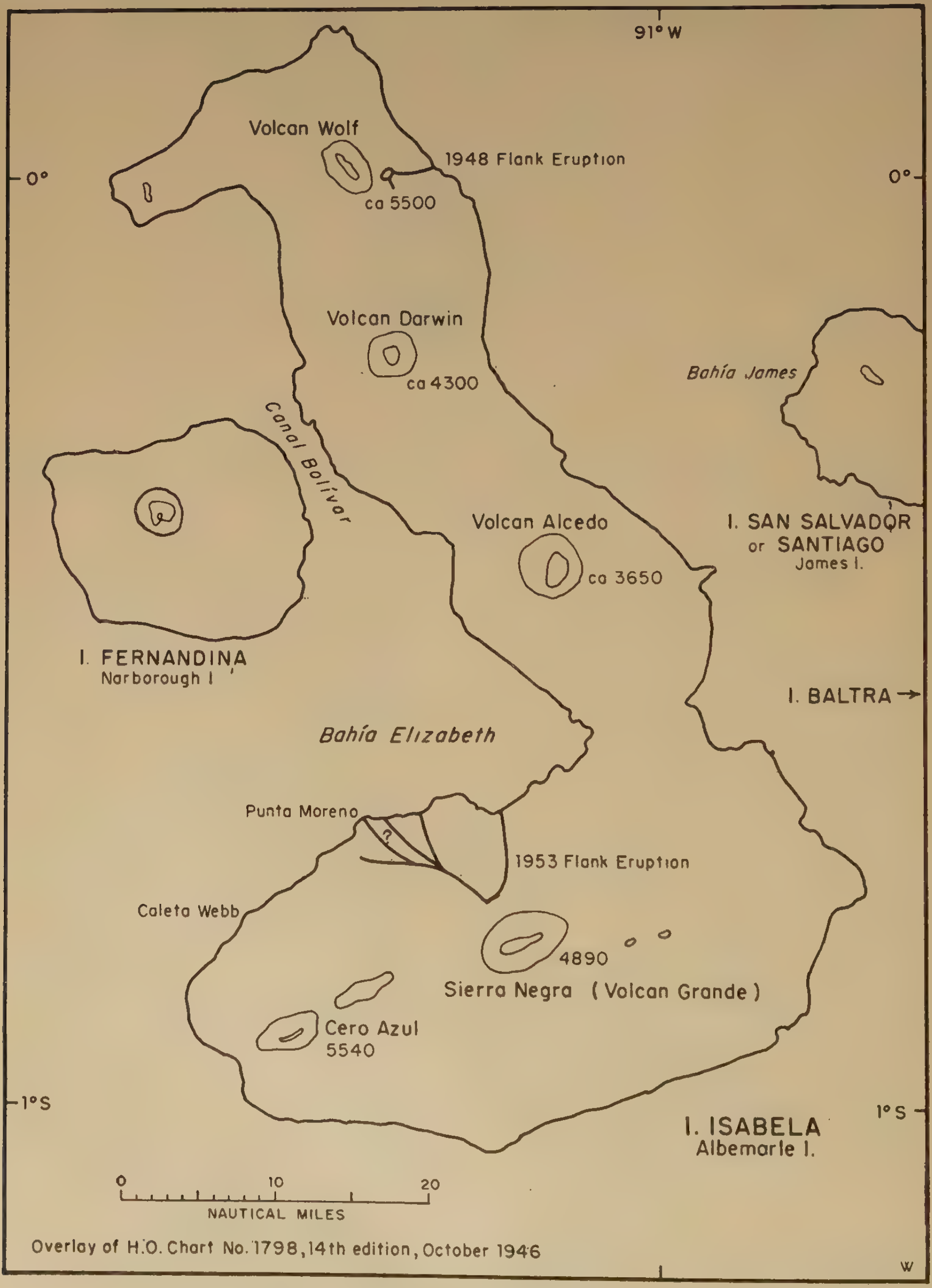
91° W
0°
0°
Volcan Wolf
1948 Flank Eruption
ca 5500
Volcan Darwin
ca 4300
Bahía James
Canal Bolivar
Volcan Alcedo
ca 3650
I. SAN SALVADOR
or SANTIAGO
James I.
I. FERNANDINA
Narborough I
I. BALTRA →
Bahía Elizabeth
Punta Moreno
?
1953 Flank Eruption
Caleta Webb
4890
Sierra Negra (Volcan Grande)
Cero Azul
5540
1°S
1°S
I. ISABELA
Albemarle I.
0
10
20
NAUTICAL MILES
Overlay of H.O. Chart No. 1798, 14th edition, October 1946
W

FIGURE 1. Location of the 1948 and 1953 flank eruptions on Isabela Island.

excellent and Captain Zeluff reported that he observed the lava flows to be located approximately as shown in Figure 1. No cone was seen at the site of the fissure, where fumarolic activity was observed. The violent phase of the eruption ceased between October 7 and the end of January, 1954. The exact date is unknown.

1948 FLANK ERUPTION OF VOLCAN WOLF

According to notations made in the log book of the "Paramount," and information obtained from Joseph Madruga, Master of the "Paramount" at that time, an eruption occurred on January 24, 1948, from a new peripheral vent near the east summit of Volcan Wolf on northern Isabela Island. To the writer's knowledge this eruption has not been previously recorded in the literature.

At the beginning of the eruption Volcan Wolf was observed from Banks Bay, about 11 nautical miles southwest of the volcano. A light-colored eruption column originating from the new vent was observed to ascend more than 10,000 feet above sea level. Throughout the time that the "Paramount" was in the vicinity of the volcano, an intermittent rumbling noise was heard. At night red incandescent bombs were seen ejected an estimated 200 to 300 feet above the vent, and Banks Bay was illuminated by the volcanic activity as brightly as during a night with a full moon.

On the 25th Madruga was flown near the eruption site in the fish-spotting Piper Cub belonging to the "Paramount." A small cone, estimated to be about 100 feet high, was seen forming on the southeastern side of the volcano near the peak, at an altitude of approximately 4,000 feet. The crater of the cone glowed cherry-red, and lava appeared to be flowing over the rim. However, the base of the cone could not be clearly seen, and consequently it is possible that the lava could have been emerging from a fissure in the cone instead of flowing over the rim. Large bombs or blocks of lava were also seen shooting skyward.

A single stream of lava from the crater of the parasitic cone was observed flowing very slowly down the flank of the volcano. Several days later, according to Madruga, other fishermen noticed that steam was rising from the shore, and it appears probable that the lava had reached the sea, about 3.5 miles from the cone. On the day of the flight a small second stream of lava was observed flowing a short distance south from the cone. The approximate position of the cone and two flows, based on the data given by Madruga, are shown in Figure 1.

The violent phase of the activity continued for at least four or five days before the "Paramount" left Isabela Island. At the end of January, or early in February, the ship was at Wolf (Wenman) Island, 85 miles north of the volcano, and a red glow from the eruption was clearly visible at night. The date of the end of the eruptive activity is not known to the writer.

REFERENCE

Report of the M. V. ROYAL PACIFIC: U. S. Hydrographic Office, Bul. 36, Sept. 5, 1953.

A METHOD FOR RECORDING RADIO TIME SIGNALS ON SEISMOGRAMS

By JERRY P. EATON

One of the most exacting requirements in seismology is the accurate timing of seismic events. For earthquake work the precision in timing currently sought is one-tenth of a second. To attain this precision an accurate time base must be provided on the seismogram. The usual procedure is to maintain a station clock, capable of running at a very uniform rate, which is equipped with contacts for marking minutes and hours on the seismogram. Time indicated by this clock is then checked periodically against the accurate radio time signals broadcast by the National Bureau of Standards Stations WWV or WWVH; by one of the U. S. Naval Radio Stations NSS, NPG, NPM, or NBA; or by similar institutions abroad.

Granted that a reliable station clock is available, the accuracy of the seismogram time base is limited by the accuracy of the radio time signal and the accuracy of the comparison of clock and radio time. Of the American stations, WWV, WWVH, and NSS broadcast time signals accurate at least to a few hundredths of a second. Signals broadcast by NPM and NPG appear to be accurate to within about one-tenth of a second. Thus, any of these stations provides time precise enough for the needs of earthquake seismology.

The most satisfactory method for comparing radio and clock time is to record the radio time signal directly on the seismogram, permitting a clock correction to be measured with at least as great a precision as that attainable in measuring individual seismic events on the seismogram. Special receivers built to close a relay in the seismograph timing circuit in response to the make-break continuous wave signals sent out by the Naval Radio Stations are usually employed for this purpose.

At the Hawaiian Volcano Observatory the need arose to adapt a small commercial communications receiver (Hallicrafters S-38C) to the task of closing a relay in response either to the NPM (Oahu) continuous wave signal or to the WWVH (Maui) modulated signal. A diagram of the rather simple and inexpensive solution to this problem is given in Figure 2. The audio frequency emf appearing across the speaker transformer primary, *T*, is rectified in a voltage-doubling circuit employing two germanium diodes, *D*. The output of this system is applied to the coil of a plate circuit relay, *Rel.* With the

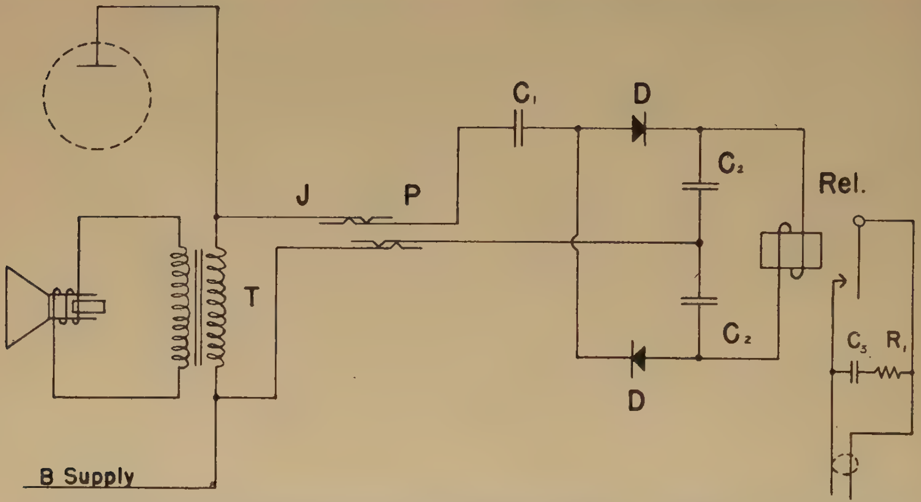

FIGURE 2. Radio adapter for recording time signals. T—Speaker transformer, J—Phone jack, P—Phone plug, C_1—$2\mu F$ capacitor, C_2—$1\mu F$ capacitor, C_3—$0.25\mu F$ capacitor, D—Germanium diode (G.E.1N91 or 1N34A), Rel.—Plate circuit relay (Potter-Brumfield LS-5, 5000Ω coil), R_1—20 to 50Ω 1 watt carbon resistor. The $1\mu F$ and $2\mu F$ capacitors preferably should be pyranol, but electrolytic capacitors are satisfactory if polarization is maintained.

circuit components used the relay closes on about 10 volts, whereas a good, strong signal develops up to 60 volts across the relay. Since this recording device requires no operating power supply, the relay, two diodes, four condensers, and one resistor required in its construction are simply mounted on a 1 × 4 × 10 inch wooden block. The device is attached to the radio circuit by means of a phone plug and jack so that it need not interfere with other use of the receiver.

Signals broadcast on any frequency which can be tuned by the receiver can be used provided the structure of the signal is suitable for recording. At the Volcano Observatory the signal from WWVH has proved to be most useful. Beginning on the hour, WWV broadcasts a 600 cps audio frequency and a one cps modulation consisting of five 1000 cps pulses at the beginning of each second. This one cps modulation, or "tick," as it sounds on the receiver, is omitted on the 59th second of each minute. During the fourth minute of the hour the audio frequency is omitted; code, voice announcements, and the one cps modulation are broadcast during this minute. At exactly five minutes after the hour a 440 cps audio frequency comes on. This frequency and the one cps modulation continue for four minutes, then the 440 cps tone goes off and another minute of code, voice announcements, and "ticks" follows. The foregoing 10-minute cycle is repeated six times per hour and continues day and night. Except for minor periodic interruptions, the WWVH signal is the same as that of WWV. The adapter described above closes the relay during period of audio frequency, code, voice announcements, and, with moderate signal strength, at each of the one cps "ticks." The timing event most clearly recordable is the return of the audio frequency after the one minute of audio frequency silence.

If photographic recording is employed the adapter relay contacts can be placed in parallel with the clock relay contacts to permit the radio time signal to be re-

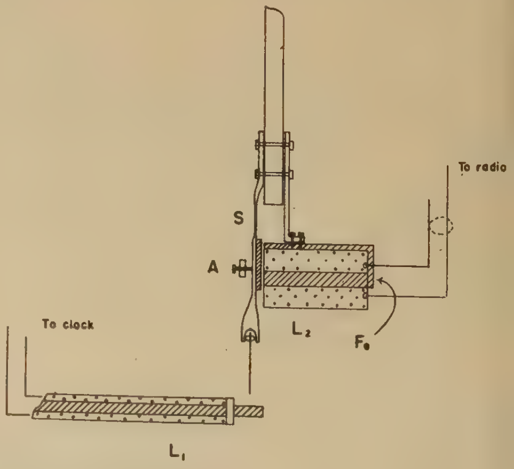

FIGURE 3. Radio time-signal marking pen for mechanical recorder. L_1—Pen lift magnet, L_2—Pen deflector magnet, Fe—Iron core and armature, A—Amplitude adjustment screw, S—Flexible pen arm.

corded by the minute-mark deflector system. If mechanical recording is used and the writing points are lifted to record time marks, it is convenient to record the radio time signal by a separate writing point which is deflected horizontally by the radio signal and is lifted from the paper by the clock signal. In practice the clock correction is obtained once a day when the record is changed. The operator drops the timing needle onto the drum and tunes the radio to record the signal. After the signal has been recorded he lifts the timing pen to avoid interference with the seismograph pens during the registration of earthquakes.

Figure 3 is a diagram of the time marker used with the mechanically recording Loucks-Omori seismographs built at the Observatory. The pen is lifted by the regular pen-lift magnet used to record clock time. In addition the pen is carried on a flexible arm which is deflected horizontally by another electromagnet controlled by the radio.

One difficulty encountered in the use of this time-marking system originated in the "feedback" through the receiver of the static generated at the relay contacts. This difficulty was overcome by employing a half-wave doublet antenna with a twin-line lead-in to the receiver; by placing a simple capacity-resistance filter across the relay contacts and near each heavy inductance in the time-signal marking circuit; and by using shielded conductors in this circuit.

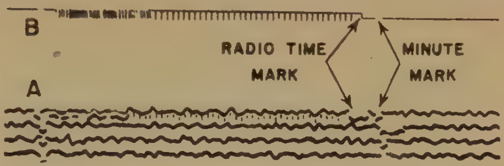

FIGURE 4. WWVH time signals recorded on an optical (A) and mechanical (B) seismograph.

Figure 4 illustrates WWVH time signals recorded on the photographic record of the Sprengnether and on the smoked-paper record of the Loucks-Omori.

HAWAIIAN VOLCANO OBSERVATORY REPORT FOR JULY-SEPTEMBER, 1954

By GORDON A. MACDONALD and JERRY P. EATON

VOLCANOLOGY

July

Earthquake activity on the island of Hawaii continued somewhat greater than usual throughout July. The seismograph at the Whitney Laboratory of Seismology, on the northeast rim of Kilauea caldera, recorded 58 quakes during the month. This is approximately twice the number usual during times of volcanic quiet. The more sensitive Sprengnether seismograph at Uwekahuna recorded a much larger number of very small earthquakes.

Most of the quakes originated within a few miles of the Whitney and Uwekahuna stations, probably beneath Kilauea caldera and the east rift zone near the caldera. On July 3, at 11:53 A.M., a strong earthquake was widely felt over the southern part of the island, and did minor damage in Hilo. Its epicenter was about a mile north of Alae Crater, five miles southeast of the caldera. J. B. Wosky, Superintendent of Hawaii National Park, reported that during and after the quake numerous heavy rock falls occurred on the seaward face of Puu Kapukapu, in the vicinity of Halape, at the coast south of Kilauea caldera. Other small shocks of this group were felt lightly in the Volcano district on July 25 and 26.

Several small earthquakes, originating farther east on the Kilauea rift zone, were recorded at the Pahoa station. A light quake, probably of local origin, was felt in central Kona on July 29.

Tilting of the ground surface at the northeastern edge of Kilauea caldera was northward at a rate only slightly greater than usual at that time of year. There did not appear to be any marked change in volcanic pressure, indicated by ground tilting.

Occasional rock falls continued on the walls of Halemaumau Crater, but their frequency during the latter half of July was somewhat less than during June. Fresh cracking of the ground surface was observed near the west, southeast, and north rims of Halemaumau.

August

Kilauea Volcano continued somewhat uneasy during August. The seismograph at the Whitney Laboratory of Seismology recorded 46 earthquakes during the month. This is somewhat more than the number normally recorded in times of volcanic quiet. Most of the quakes originated beneath or near Kilauea caldera. Tilting of the ground at the northeastern rim of the caldera was northward at a rate slightly greater than usual at that season. There was no indication of any decrease of volcanic pressure beneath Kilauea.

A sharp earthquake was felt in Kona at 11:27 P.M. on August 1. Its origin was within a few miles of the seismograph station at Konawaena school, probably on the Kealakekua fault near the northern edge of Kealakekua Bay. At 2:27 P.M. on August 7 a strong quake originated beneath Kilauea caldera. It was felt by many persons in the Volcano area, and by some in Hilo and Kona. A moderate quake at 11:16 P.M. on August 30, felt by residents of the Volcano area, also originated beneath Kilauea caldera.

September

The seismograph at the Whitney Laboratory of Seismology recorded 94 earthquakes during the month, approximately three times the number recorded during normal times of volcanic quiet. During the week starting September 12 alone, 56 quakes were recorded. Most of the earthquakes appear to have originated beneath the Kilauea caldera area or the adjacent part of the east rift zone. Several during mid-September appeared to originate at depths of 25 to 30 miles beneath the caldera or the nearby slope of Mauna Loa. One at 2:43 A.M. on September 13 was felt in Hilo.

Several quakes were felt in Kona during early September. These originated on the western slope of Mauna Loa, probably on the Kealakekua fault. No other signs of uneasiness of Mauna Loa were noted.

Tilting of the ground at the northeast rim of Kilauea caldera was approximately normal in direction and amount for that season of the year. Thus no marked change in volcanic pressure beneath Kilauea was indicated.

Neither during the May-June eruption of Kilauea, nor in the four months following the eruption, has there been any indication of reduction of volcanic pressure beneath Kilauea Volcano. Magma appears probably to be still standing at a high level in the conduit. Under such conditions, eruption may occur with little or no warning other than the numerous earthquakes that indicate continued uneasiness of the volcano.

SEISMOLOGY

Local Earthquake Data, July-September, 1954

(Based on Bosch-Omori seismograph on northeast rim of Kilauea caldera)

Week Beginning	Minutes of Tremor	Very Feeble	Feeble	Slight	Moderate	Strong	Total	Local Seismicity*
July 4	2	4	0	0	0	0	6	2.50
11	10	15	2	0	0	0	27	12.00
18	6	6	1	0	0	0	13	5.50
25	1	9	0	2	0	0	12	8.75
Aug. 1	1	9	0	1	0	0	11	6.75
8	6	6	0	0	0	2	14	12.50
15	1	4	0	0	0	0	5	2.25
22	3	5	2	2	0	0	12	9.25
29	7	7	0	0	1	0	15	8.25
Sept. 5	3	4	1	0	0	0	8	3.75
12	32	19	3	2	0	0	56	21.00
19	9	9	0	1	0	0	19	8.75
26	5	8	1	0	0	0	14	6.25

* For definition of local seismicity see Volcano Letter 371 or 512. Each local earthquake is assigned a seismicity value according to its strength, as follows: tremor, 0.25; very feeble, 0.5; feeble, 1.0; slight, 2.0; moderate, 3.0; strong, 4.0. These values are totaled to give the weekly local seismicity. Continuous volcanic tremor is ignored in the calculation. The strength assigned to the earthquake depends on the double amplitude of the maximum oscillation it causes on the Bosch-Omori seismograph, as follows: tremor, less than 0.5 mm.; very feeble, 0.5 to 4 mm.; feeble, 4 to 11 mm.; slight, 11 to 25 mm.; moderate, 25 to 60 mm.; strong, greater than 60 mm.

Table of Tilt at Seismograph Stations on Rim of Kilauea Caldera

Week Beginning	Whitney Station (Northeast rim)		Uwekahuna Station (West rim)	
	Amount	Direction	Amount	Direction
July 4	0.4″	S 56° W	1.8″	S 31° E
11	1.0″	N	1.3″	S
18	1.3″	N 30° E	2.7″	S 21° E
25	0.4″	N 18° W	3.0″	N 19° W
Aug. 1	0.8″	N 18° W	2.2″	N 26° W
8	1.0″	N 21° W	1.7″	N 22° W
15	0.9″	N 56° E	0.3″	N
22	0.4″	S 33° W	0.4″	N 45° E
29	1.3″	N 21° E	2.9″	S 12° E
Sept. 5	0.4″	N 18° E	2.1″	S 26° E
12	1.0″	N 53° E	1.0″	S 18° W
19	0.2″	N 45° W	2.3″	N 17° W
26	0.6″	S 37° E	1.0″	N

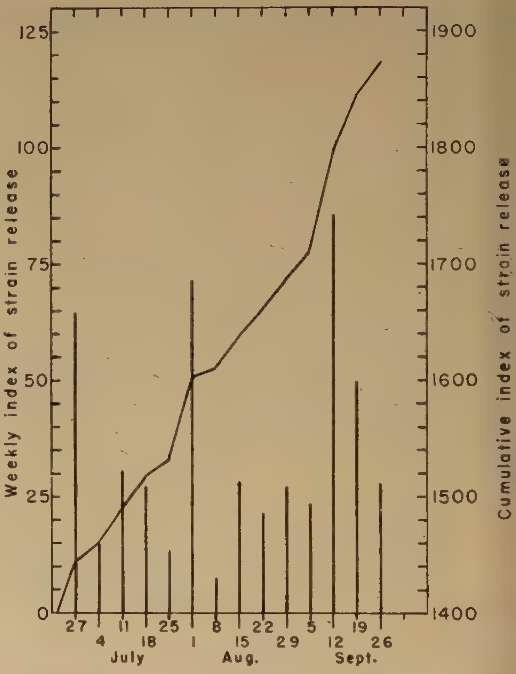

FIGURE 5. Graph showing weekly strain release index (vertical bars) and cumulative strain release index (continuous curve) for the Kilauea caldera region from late June through September, 1954. An increase in steepness of rise of the cumulative curve represents an increase in rate of strain release through earthquakes.

Local Earthquakes

The data for the following local earthquakes were determined from seismographs on the islands of Hawaii and Maui operated by the Hawaiian Volcano Observatory. The number preceding each quake is the serial number for the current year. Only earthquakes classed as feeble or larger are included in the list. Many very feeble quakes, to which serial numbers are assigned also, are omitted. Locations given are epicenters. Except where otherwise indicated, the times given are arrival times at the Uwekahuna station, on the western rim of Kilauea caldera. They are stated in Hawaiian standard time, which is 10 hours behind Greenwich civil time. The intensity rating (Feeble, Moderate, etc.) given is based on the Bosch-Omori seismograph at the Whitney Laboratory of Seismology. If the intensity was greater at one of the other stations, the name of that station and the intensity rating there are given in parentheses after the rating at the Whitney Station.

461. July 1, 09:06, feeble (Mauna Loa, moderate). Felt in Hawaii National Park. About 10 km deep under Kilauea caldera.

462. July 2, 06:00, feeble. Kilauea caldera.

465. July 3, 11:52:35, strong. Felt quite generally over southern half of Hawaii. About 12 km deep under Alae Crater on the east rift of Kilauea.

476. July 11, 12:07:26, feeble. East rift of Kilauea near Napau Crater.

486. July 15, 17:10:07, feeble. Kilauea caldera.

500. July 22, 13:35 (Pahoa), not recorded at Kilauea (Pahoa, feeble). East rift of Kilauea near Pahoa.

501. July 22, 15:38 (Pahoa), not recorded at Kilauea (Pahoa, feeble). East rift of Kilauea near Pahoa.
502. July 22, 20:36:50, feeble. Kilauea caldera.
506. July 25, 18:17:55, slight. Felt in Hawaii National Park. Near Mauna Loa seismograph station about 10 km deep.
508. July 26, 00:51:44, slight. Felt in Hawaii National Park and in central Kona. Along the Kaoiki fault west of the Observatory at a depth of 10 km.
520. Aug. 1, 23:27:48, not recorded at the Whitney Laboratory (Kona, feeble). Felt in central Kona. Central Kona.
521. Aug. 2, 13:40:33, strong. Felt in Volcano area. About 15 km deep under Alae Crater on the east rift of Kilauea.
523. Aug. 7, 14:26:17, strong. Felt generally over central Hawaii. 25 km deep under Kilauea caldera.
536. Aug. 16, 04:45:33 (Pahoa), not recorded at Kilauea (Pahoa, feeble). East rift of Kilauea near Pahoa.
540. Aug. 18, 07:13:56, slight. Kilauea caldera.
542. Aug. 20, 01:58:54, feeble. East rift of Kilauea near Makaopuhi Crater.
559. Aug. 30, 23:17:04, moderate. Felt in Volcano area. 20 km deep under Makaopuhi Crater.
564. Sept. 1, 15:17:49, not recorded at the Whitney Laboratory (Kona, slight). Felt in central Kona. Central Kona.
570. Sept. 7, 14:48:36, not recorded at the Whitney Laboratory (Pahoa, feeble). East rift of Kilauea near Pahoa.
576. Sept. 8, 23:03:52, feeble. Kilauea caldera.
588. Sept. 12, 21:58:59, slight. Under Kilauea caldera at a depth of 20 km.
590. Sept. 12, 23:08:26, tremor (Mauna Loa, very feeble). This very feeble earthquake is included in the list because it is typical of about 250 earthquakes (tremor and very feeble in strength) which originated on Sept. 12 and Sept. 13 at a depth of about 45 km below the southeast flank of Mauna Loa between the Mauna Loa seismograph station and the Volcano Observatory.
595. Sept. 13, 02:42:53, feeble. Felt in Hilo. 5 km east of Puu Kapukapu along south coast of Kilauea at a depth of about 15 km.
598. Sept. 13, 18:22:05, feeble. 20 km deep under east rift of Kilauea near Makaopuhi Crater.
602. Sept. 15, 01:23:06, feeble. Kilauea caldera.
604. Sept. 16, 08:15:04, slight. Kilauea caldera.
622. Sept. 22, 00:19:35, slight. Kilauea caldera, 15 km deep.
630. Sept. 25, 21:12:07, not recorded at the Whitney Laboratory (Pahoa, feeble). East rift of Kilauea near Pahoa.

Distant Earthquakes

The following earthquakes of distant origin were recorded on the seismographs of the Hawaiian Volcano Observatory. Locations of the epicenters and the magnitudes are from the notices of Preliminary Determinations of Epicenters published by the U. S. Coast and Geodetic Survey. The time given is that of the first detectable emergence of the quake on the Sprengnether vertical seismograms, in Hawaiian standard time.

July 1, eP 16:51, 13½° N., 123½° E. Southeastern Luzon, P. I. Many casualties and extensive property damage. Mag. 6¾–7¼.
July 5, eP 22:13:27.6, 46½° N., 153½° E. Kurile Islands. Mag. 6½–7.
July 6, eP 01:20:35.3, 39½° N., 118½° W. Near Fallon, Nevada. Several injured and moderate property damage. Mag. 6¾–7.
July 6, eP 12:14:58.6, Fallon, Nevada, aftershock. Mag. 6¼–6¾.
July 17, eP 23:17:39.4, 35½° N., 140½° E. Near east coast of Honshu, Japan. Felt. Mag. 6½.
July 30, eP 15:12:46.3, 39° N., 140° E. Ningsia province, China. Mag. 6½.
July 31, eP 17:33:41.0, 3° S., 140° E. Northern New Guinea.
Aug. 4, eP 22:57:26.1, 52° N., 176° E. Rat Islands, Aleutian Islands. Mag. 6–6¼. Depth 60 km.
Aug. 9, eP 09:25:26.7, 53° N., 161° E. Off east coast of Kamchatka. Mag. 6½–6¾. Depth 60 km.
Aug. 17, iP 18:50:26.9, 21½° S., 176° W. Tonga Islands. Mag. 7–7¼. Depth about 150 km.
Aug. 23, eP 19:58:52.1, 39½° N., 118½° W. Near Fallon, Nevada. Minor property damage at Fallon and Lovelock. Mag. 6½–6¾.
Aug. 27, eP 01:04:41.5, 24½° N., 143° E. Volcano Islands. Mag. 6¾. Depth about 100 km.
Aug. 31, eL 12:30, Fallon, Nevada, aftershock. Mag. 5½–6½.
Sept. 2, eP 09:00:08.4, 10° S., 166° E. Santa Cruz Islands. Depth about 100 km.
Sept. 3, eP 17:39:32.9, 3° S., 139½° E. Northern New Guinea. Mag. 6¼. Depth about 60 km.
Sept. 4, eP 21:54:18.5, 19° S., 176° E. Fiji Islands region. Mag. 6½.
Sept. 6, eP 08:39:35.0, 51° N., 158° E. Near southeast coast of Kamchatka. Mag. 6½. Depth about 60 km.
Sept. 12, eP 16:18:01.7, 21° S., 175½° W. Tonga Islands. Mag. 6¾. Depth about 150 km.
Sept. 15, iP 08:03:27.2, 18° S., 178½° W. Fiji Islands. Mag. 7. Depth about 600 km.
Sept. 17, iP 01:11:18.3, 20½° S., 177½° W. Fiji Islands region. Mag. 7–7¼. Depth about 250 km.
Sept. 19, eP 14:52:10.8, 1½° S., 120½° E. Celebes. Mag. 5¾–6.
Sept. 30, eP 17:03:21.0, 11° S., 166° E. Santa Cruz Islands. Mag. 6½–7.

VOLCANO NOTES AND NEWS

ERUPTION OF NGAURUHOE

Ngauruhoe Volcano, on the North Island of New Zealand, broke into violent eruption on June 4. The volcano is a conical mountain 7,515 feet in altitude, 175 miles southeast of Auckland. The following information was furnished by James Healy, New Zealand Government volcanologist, and Brenda Bishop, Secretary of the Pacific Science Council.

The volcano had been in activity for some time, sending big ash clouds high into the air. On the morning of June 4 the entire top of the mountain was reported to be aglow even in daylight. Flying over the volcano, Healy found the crater full of lava, with spurts of orange-red lava going some 500 feet into the air, and two lava flows moving down the slopes of the mountain. One flow came down directly on top of the lava flow of 1949, and the other a little farther south. Very little ash was being liberated. The lava flows were visited on June 5. They had nearly come to rest, but large blocks were rolling down the mountainside following numerous explosions at the crater. On June 6 activity was more explosive and more ash was being liberated. The explosive phase continued for several days, but on a lesser scale than in 1949.

Another increase of activity occurred on the night of June 9. Spectacular flows of lava were visible from Chateau Tongariro during the evening, but by 3 A.M. on June 10 the spurt of activity was nearly over. The lava flow is reported to be of aa type, and in places to exceed 70 feet in thickness. A cinder cone built in the crater of the volcano was reported to have reached a height of 200 feet on June 9, and to be breached toward the west where the lava flows escaped.

In September Ngauruhoe was still active. Strong explosions took place on the night of September 2. Several lava flows have been reported on the flanks of the cone during June, July, and August. One of the largest occurred on August 18.

Ruapehu Volcano, 12 miles southwest of Ngauruhoe, was reported steaming in early October. Healy flew over the crater on October 8, and reported that the steam was thick enough to obscure part of the crater lake. Ruapehu Volcano erupted in 1895. Another eruption in 1945 caused the temporary drying up of the crater lake. During that eruption a small lava dome was built in the crater.

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